PALEOENVIRONMENTAL INTERPRETATION OF LATE GLACIAL AND POST-GLACIAL FOSSIL MARINE MOLLUSCS, EUREKA SOUND, CANADIAN ARCTIC ARCHIPELAGO

A Thesis Submitted to the College of

Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Master of Science

in the Department of Geography

University of Saskatchewan

Saskatoon

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ABSTRACT

A total of 5065 specimens (5018 valves of bivalve and 47 gastropod shells) have been identified and classified into 27 species from 55 samples collected from raised glaciomarine and estuarine sediments, and glacial tills. The bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* are the most common species. Our samples record the dominance of infaunal suspension-feeders that are most abundant on soft substrates typically occurring in nearshore environments. The dominance of bivalves with respect to gastropods reflects an averaged record of the fossil assemblages inhabiting the high latitude nearshore environments. Six unique associations, which are comparable to the composition of modern communities inhabiting in fiords and on continental shelf from Canadian high arctic, and three distinctive taxa groups (deposit feeders, suspension-feeders, and rare taxa) are recognized by cluster analysis and Multidimensional Scaling conducted on presence-absence data. The trophic composition of paleocommunities in this study is as follows: suspension-feeders > deposit feeders > carnivores > browsers. The occurrence of *Mya pseudoarenaria* in fossil assemblages indicates an age of the fossils around early Holocene.

Most of the samples are not substantially transported nor significantly reworked. Shell disarticulation and fragmentation can result from sea ice scouring of the seafloor and the development of permafrost in raised marine sediments. The degree of shell disarticulation for the four most common taxa is generally low which likely reflects high sedimentation rates and rapid burial in nearshore environments, especially those from glaciomarine silts and estuarine deposits. Four common species exhibit different

preservation potential based the degree of fragmentation and disarticulation (*Serripes* < *Mya* < *Hiatella* < *Astarte*). Shells with high (or low) degree of fragmentation for single species (i.e. *Hiatella*) also correspond to different energy conditions of the associated sediments facies from which the shells are recovered. The general absence of strongly bioeroded or encrusted shells among samples suggests rapid burial of the shells with only limited exposure on the sediment surface, or the absence of grazing, boring or encrusting taxa in the environment that is dominated by infaunal habit of most of the taxa represented in the shell assemblages.

Four taphofacies are recognized by cluster analysis on the basis of four taphonomic variables (fragmentation, corrasion, bioerosion, and encrustation) characterized by poor preservation, fair preservation, fair-good preservation, and fair preservation with poor corrasion respectively. Faunal succession and paleo-marine environments during the deglaciation in early Holocene are reconstructed from the seven sedimentation facies (glacial, beaches, shallow marine, proglacial, shallow marine or estuarine - pebbly sand and gravel with algal debris, shallow marine or estuarine - pebbly silt with algal debris, shallow marine or estuarine - interbedded silt and sand).

ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. Alec Aitken for his tremendous patience, tolerance, guidance, and good humor throughout this work. Alec has cheerfully given too much of his time, energy, and thought to this thesis, and for this and more I am very grateful. I also wish to thank my advisory committee Dr. Xulin Guo for her help on statistical analysis and encouragement, and Dr. Bill Archibold for his insights.

I wish to extend my sincere thanks to the many people who have supported and encouraged me in this work. I thank Ms. Jennifer Murray for her introducing me to taphonomic analysis. I thank the Museum of Nature for helping me on mollusc species identification. I also thank my graduate colleagues for their always kind assistance and encouragement.

I would like to thank the Department of Geography at University of Saskatchewan and Natural Sciences and Engineering Research Council (NSERC) for the financial assistance.

Finally, I wish to give my particular thanks to my parents for their support and understanding on my study abroad. This thesis could not have been completed without the tremendous love and support of my fiancé, HanJie, throughout my graduate program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Introduction

The study of marine macrobenthos from arctic and sub-arctic regions has been a topic of scientific interest since 1940s. Among the animals living on the seafloor of polar oceans, bivalve molluscs are commonly best preserved as marine fossils. Scientists use the information derived from the comparison of modern and fossil marine mollusc communities to understand the nature of post-glacial environmental change (Hillaire-Marcel, 1980; Mode, 1985; Thomsen and Vorren, 1986; Rodrigues, 1988; Dyke *et al.*, 1996a; Simonarson *et al.*, 1998). Paleoenvironmental interpretation of fossil marine macrobenthos in polar regions will help us to understand and prepare for the future changes in high latitude marine environments.

Molluscs recovered from Tertiary and Quaternary deposits have been used to follow periods of interchange and colonization between the basins of the Atlantic and the Pacific oceans. Lying between these two oceans, the Arctic is a critical region for paleoenvironmental study in polar regions (Gordillo and Aitken, 2000). Two geological events appear to have had an important impact on the evolution of Canadian Arctic molluscan faunas: 1) during the Tertiary, the opening of the Bering Strait at 3.5-3.0 Ma ago, and 2) during the Late Quaternary, when deglaciation of North America, Europe and Asia, re-established the connection between the Pacific and the Atlantic oceans (Gordillo and Aitken, 2000). The molluscs inhabiting nearshore environments in the Canadian Arctic Archipelago, therefore, provide a key to reconstructing

paleoenvironment and to evaluating changes in faunal composition during the Quaternary period.

1.2 Significance of the Study

This research program integrates the study of modern aquatic biology with the analysis of the sedimentology and paleontology of Late Pleistocene and Holocene glaciomarine and nonmarine (i.e. glacial tills) sediments to the study of the nature of environmental change during the Late Quaternary period in the Canadian High Arctic. The knowledge derived from the proposed research will contribute directly to our understanding of the nature of past environmental change in a region of Canada most likely to be impacted by ongoing environmental change. This information will assist in the assessment of potential future change in the functioning of marine ecosystems in the Canadian Arctic. This thesis research will focus on the paleoecology of marine benthos and test the hypothesis that variations in glacier and sea ice cover throughout the Late Pleistocene and Holocene (last 12,000 years) have controlled the composition of benthic communities in the Canadian Arctic Archipelago through their influence over variations in the temperature and salinity of ocean waters and the flux of clastic sediment to nearshore environments. The object of my research project is to reconstruct the paleoecology of Late Quaternary nearshore marine environments in the Canadian Arctic.

1.3 Research Objectives

1.3.1 Holocene Environmental Change in the Canadian High Arctic

It is evident that there have been great variations in the Holocene sea ice cover, glacier margins, and temperature within the Queen Elizabeth Islands since the last deglaciation of the Queen Elizabeth Islands at about 10 ka BP (Stewart and England, 1983; Bradley,

1990; Hein *et al.*, 1990; Koerner and Fisher, 1990; Hein and Mudie, 1991; Evans and England, 1992; Fisher *et al.*, 1995; Dyke *et al.*, 1997; Dyke *et al.*, 1999; Bourgeois *et al.*, 2000; Dyke and England, 2003). Proxy data, such as driftwood abundance, whale bone abundance, and meltwater production, have been studied to provide information about the Holocene environmental change (Table 1.1). The driftwood was transported via the Transpolar Drift across the northern and central Canadian Arctic Archipelago to western Wollaston Peninsula for the early Holocene into the mid-Holocene (11.1 to 4.7 ka BP) (Dyke *et al.*, 1996b). The changes of driftwood abundance recorded the variations of the sea ice cover within the Canadian Arctic Archipelago during the early and mid- Holocene. The changes in the geographic range of the bowhead whale were studied by Dyke *et al*. (1996b) to reconstruct sea ice cover minima in the Canadian Arctic Archipelago. The changing amounts of summer meltwater recorded by melt layers in Canadian high arctic ice cores can be an indicator of Holocene glacier margin development and summer climate (Bradley, 1990; Hein *et al.*, 1990; Koerner and Fisher, 1990; Fisher *et al.*, 1995). These proxy data, though recording information about climate change of a different nature, can be combined to illustrate an image of the Holocene climate change (Bradley, 1990).

The last deglaciation of the Queen Elizabeth Islands began about 10 ka BP and was associated with a marked climatic amelioration. The Holocene period is divisible into four climatic periods based on the proxy data listed in Table 1.1 (Stewart and England, 1983; Bradley, 1990; Koerner and Fisher, 1990; Hein and Mudie, 1991; Evans and England, 1992; Fisher *et al.*, 1995; Dyke *et al.*, 1996b; Dyke *et al.*, 1997; Dyke *et al.*, 1999; Bourgeois *et al.*, 2000; Dyke and Savelle, 2000, 2001; Dyke and England, 2003).

First, the early to middle Holocene (10.5 to 6 ka BP) was the warmest interval with temperatures comparable to, if not higher than, temperatures of the 20th century). The early Holocene was characterized by large quantities of summer meltwater production from alpine glaciers. Initial driftwood incursion into these channels occurred between 9 to 8.5 ka BP, with maximum of driftwood abundance on beaches recorded between 6 to 5.75 ka BP. Whale bone is recorded from beaches beginning at 10.9 ka BP. The presence and high abundance of driftwood and whale bone recorded from beaches during this interval indicates considerable open water in the inter-island channels within the study area and a prolonged climatic amelioration (Dyke *et al.*, 1996b; Dyke *et al.*, 1997). The middle Holocene thermal maximum may reflect a lag in the response of the environment and of some proxies in recording changes in the regional climate.

The proxy data indicate fluctuating sea ice conditions occurred during the interval from 6 to 3 ka BP. A sharp decline in the supply of driftwood and whale bone to inter-island coastlines characterizes the interval from 6 to 5 ka BP, and is followed by an interval of increased driftwood and whale bone abundance between 5 to 3 ka BP (Dyke *et al.*, 1996b). These data indicate that summer sea ice cover was more extensive early in the middle Holocene and that summer climate had ameliorated later in this period, allowing for more extensive open water conditions. There is no corroborating evidence for these changing environmental conditions preserved in the summer melt record from the adjacent ice sheets for this time period (Bradley, 1990; Koerner and Fisher, 1990; Fisher *et al.*, 1995).

Table 1.1 Proxy data for Holocene environmental change in the eastern Canadian High Arctic.

Time Scale (ka BP)	Driftwood Abundance	Whale Bone Abundance	Glacier Margins and Meltwater Production	Regional Temperature
0			- Meltwater production is increasing, ice shelves are breaking and melting - Glaciers are retreating	- Warmer temperatures
0.1	- Driftwood supply increased (to its greatest abundance)		- Glaciers advanced to post-glacial maximum positions	- Coldest temperatures in the Holocene (Neoglacial)
0.4	- Sea ice cover reduced significantly			
0.5	- Driftwood supply decreased - Sea ice cover increased	- Whale bone was excluded - Sea ice cover increased	- Meltwater production is decreasing - Glaciers margins are advancing	- Colder temperatures
3	- Driftwood supply was moderate and reach peak abundance at 3 to 2.5 ka BP	- Whale bone abundance increased - Sea ice cover was reduced		
5	- Sea ice cover was reduced			
	- Driftwood supply decreased sharply at 5.25 ka BP	- Whale bone excluded		
5.25	- Driftwood supply increased (to a peak abundance at 6 to 5.75 ka BP)	- Sea ice cover became extensive	- Meltwater production increasing	- Warmest temperatures in the Holocene
6				
8.5	- Sea ice cover reduced	- Whale bone abundance increased	- Glacier margins are retreating	
8.9		- Sea ice cover reduced		
10.5				

References:
Maxwell (1980), Stewart and England (1983), Bradley (1990), Koerner and Fisher (1990), Hein and Mudie (1991), Evans and England (1992), Fisher *et al.* (1995), Dyke *et al.* (1996b), Dyke *et al.* (1997), Bourgeois *et al.* (2000), Dyke and England (2003), Mueller *et al.* (2003).

A climatic deterioration occurred in the late Holocene (from 3 to 0.1 ka BP), characterized by extensive sea ice cover and colder temperatures. This "Neo-glacial" period was the coldest period of the entire Holocene (Bradley, 1990). Ice shelves

formed and alpine glaciers advanced to post-glacial maximum positions during this period in response to the cold temperatures. Multiple advances of some glaciers occurred in this interval (Evans and England, 1992). Driftwood penetration declined and the whale bone was excluded from the inter-island channels from 3 ka BP (Dyke *et al.*, 1996b; Dyke *et al.*, 1997), indicating increasing severe sea ice conditions in the study region.

Lastly, the period since 1925 has exhibited a distinct increase in temperature, leading to negative mass balances for glaciers and ice sheets throughout the eastern Canadian Arctic Archipelago (Koerner and Fisher, 1990). This period is the warmest interval recorded in the last millennium (Bradley, 1990). The ice shelves are presently breaking up and melting in response to the recent warming. Recently, for example, the Ward Hunt Ice Shelf Field (83°N, 74°W) has broken in two over the period 2000 to 2002 as recorded by RADARSAT imagery, with additional fissuring and further ice island calving (Mueller *et al.*, 2003). This break-up results from a significant rise in mean annual air temperature (~2°C) from 1967 to the present in the High Arctic region (Maxwell, 1980; Mueller *et al.*, 2003).

1.3.2 The Role of Glaciers and Sea Ice Cover in the Canadian Arctic Archipelago

In the high arctic regions, research on modern and fossil marine mollusc communities (e.g., Curtis, 1975; Thomson *et al*., 1986; Aitken and Gilbert, 1996; Dyke *et al*., 1996a; Aitken and Bell, 1998; Gordillo and Aitken, 2000, 2001) indicate that the species composition and structure of nearshore marine macrofaunal communities are significantly influenced by glacier ice and sea ice. The glacier and sea ice cover, in combination with terrestrial runoff, has varied through the Holocene, and has modified

the temperatures and salinities of nearshore waters. In the Canadian Arctic Archipelagoes, *Portlandia* association (dominated by *Portlandia arctica* alone) is common in fine-grained, ice proximal glaciomarine sediments deposited at the first stage of deglaciation characterized by rapid retreat of sea ice margins, limiting marine primary production, variable salinities, and rapid clastic sedimentation in glacial meltwater; A restricted Arctic association dominated by *Hiatella arctica* and *Mya truncata* can be found in the ice-proximal waters during deglaciation and in the period of early postglacial characterized by reduction of clastic sedimentation, increasing of marine primary production and the supply of labile organic matter to the benthos; A more diverse association with addition of suspension-feeding bivalves such as *Astarte borealis*, *Macoma calcarea*, *Clinorcardium ciliatum*, *Serripes groenlandicus*, *Musculus spp.*, *Nuculana pernula*, *Mya pseudoarenaria*, etc., appeared in nearshore environments during the period of postglacial characterized by development of modern marine environments associated with restricted influx of meltwater and clastic sediments, and large organic matters from marine sources (Dyke *et al.*, 1996a; Gordillo and Aitken, 2001).

The activities of glacier and sea ice also play distinct roles in affecting the texture of substrates inhabited by molluscs. Ice-rafted cobbles create "faunal islands" on the seafloor that commonly support many epifaunal organisms (Dale *et al.*, 1989). Direct freezing of organisms during ice foot development, abrasion by drift ice during breakup in early summer, and physiological stress from lower salinities created by melting sea ice and icebergs in summer contribute to the absence of a shallow-water macrofauna in high arctic fjords (Reimnitz *et al.*, 1992; Aitken and Gilbert, 1996; Conlan *et al.*, 1998).

Primary productivity may affect the amount of food available to benthic animals. The prolonged presence of sea ice shortens the period of primary production therefore limiting the food resources available to the benthos (Dale *et al.*, 1989). Marine macrofaunal succession preserved in Late Quaternary sediments exhibits patterns that reflect the activity of glaciers and sea ice and the supply of organic matter to the benthos (Syvitski *et al.*, 1989; Aitken, 1990; Dyke *et al.*, 1996a; Aitken and Bell, 1998; Gordillo and Aitken, 2000, 2001).

1.3.3 Preservation Pattern in Fossil Molluscs Assemblages of Marine Molluscs and Quaternary Paleoenvironmental Reconstruction in Canadian Arctic Archipelago

The fossil record can yield a great deal of ecological information relating to the habitats occupied by fossil molluscan associations if the nature of preservational biases is understood. The preservation quality of a particular fossil specimen is largely determined by biostratinomic and early diagenetic processes which occur in or near the original sedimentary environments and are characteristic of that environment (Brett and Baird, 1986). Studies of taphonomy (fossil preservation) suggest that macrofaunal assemblages as a whole most commonly represent parautochthonous assemblages whose specimens have undergone minor taphonomic modification prior to burial on the seafloor (Gordillo and Aitken, 2000, 2001; Kidwell, 2001). Examination of patterns of fossil preservation and macrofaunal succession, and the community structure of modern marine benthos, can be combined to reconstruct Late Quaternary marine environments. Molluscs have been incorporated into paleoenvironmental reconstructions in many studies, for examples, the studies at Pangnirtung Fiord by Aitken *et al*. (1988),

northeastern Greenland by Simonarson *et al*. (1998), Norwegian continental shelf by Thomsen and Vorren (1986), and Champlain Sea basin by Rodrigues (1988), etc.

The objectives of this research discussed above can be summarized as three research questions, which involve to the pattern of macrofaunal succession preserved in the sediments, the influence of environmental factors on the macrofaunal succession, and the pattern of mollusc shell preservation observed in this study.

Question 1. The work of Thomsen and Vorren (1986), Dyke *et al.* (1996a), and Gordillo and Aitken (2001) indicates that macrofaunal succession occurs during the last deglaciation and post-glacial period throughout the Canadian Arctic Archipelago and on the Norwegian continental shelf. What is the pattern of macrofaunal succession preserved in Late Pleistocene and Holocene glaciomarine sediments on southeastern Axel Heiberg Island, and does it conform to patterns observed elsewhere in the Canadian Arctic Archipelago?

Question 2. The work of Syvitski *et al*. (1989) and Dyke *et al*. (1996a) indicates that changes in the species composition of mollusc assemblages is related to variations in the physical environment such as variations in sea ice cover, retreat and/or advance of glaciers, and discharge of fresh water, sediment and organic matter into nearshore environments throughout the post-glacial period. Does the pattern of macrofaunal succession observed in this study correspond to documented changes in nearshore environments in the eastern Canadian Arctic?

Question 3. The pattern of shell preservation observed by Aitken (1990) on Baffin Island and Gordillo and Aitken (2001) on Prince of Wales Island indicates that infaunal

suspension bivalves and epifaunal gastropods inhabiting nearshore environments within fjords and on continental shelves exhibit the greatest preservation potential. Does the pattern of shell preservation conform to the patterns observed elsewhere in the Canadian Arctic?

CHAPTER 2 LITERATURE REVIEW

2.1 Regional Studies and Field Methods

The marine biology of the arctic and sub-arctic regions has been the subject of several studies (see Table 2.1), specifically the fjords along the eastern coast of Baffin Island (Thomson, 1982; Stewart *et al.*, 1985; Dale *et al.*, 1989; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993), the western coast of Greenland (Vibe, 1939, 1950; Schmid and Peipenberg, 1993) and the Canadian Arctic Archipelago and Beaufort Sea (Curtis, 1975; Hunter and Leach, 1983; Thomson *et al.*, 1986; Dale *et al.*, 1989; Carey, 1991; Conlan *et al.*, 1998). The biology of Canadian high arctic fjords, however, remains poorly investigated (Curtis, 1975; Dale *et al.*, 1989). Aitken and Gilbert (1996) examined the distribution of molluscs in Expedition Fjord, Axel Heiberg Island, and defined two molluscan associations inhabiting shallow-water and deep-water environments, respectively, within the fjord. Gordillo and Aitken (2000, 2001) studied fossil marine mollusc assemblages from Prince of Wales, Somerset, Devon, Axel Heiberg, and Ellesmere Islands. They found that fossil mollusc assemblages share the same common species with modern nearshore benthic communities.

A wide range of techniques, employing sampling apparatus identical to those used in other marine regions, has been used to study the arctic benthos (Holme and McIntyre, 1971; Curtis, 1975). Originally, the "naturalist's dredge" provided nearly all of the samples of bottom fauna from the polar seas. Since the early 1930's, a variety of sampling devices have also been utilized to obtain quantitative estimates of the species composition and abundance of the benthos. Foremost among these is the bottom grab (e.g. Van Veen or Petersen grab), a steel-jawed instrument that is designed to sample

the fauna and sediments from a small area of known dimensions (usually less than $0.5m^2$) (Curtis, 1975). The bottom grab has been extensively employed for field studies where fine sediments such as mud or sand occur. On hard, rocky seabeds and on coarse substrates such as gravel, a variety of heavy dredging gear is used, often supplemented by visual aids such as bottom photography or closed-circuit television. Manned submersibles and SCUBA divers have proven useful in contemporary studies (Curtis, 1975; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993). However, the Van Veen grab is the most frequently used apparatus to take samples in diverse sediments. Convenient manual tools such as the mason's trowel are commonly used to obtain bulk samples of raised marine sediments for paleoecological research.

Table 2.1 Regional studies of modern arctic marine benthos.

Regions	**Publications**
Baffin Island	Curtis, 1975; Thomson, 1982; Dale *et al*, 1989; Syvitski *et al*, 1989; Aitken, 1990; Aitken and Fournier, 1993.
Greenland	Vibe, 1939, 1950; Curtis, 1975; Stewart *et al*, 1985; Schmid and Piepenburg, 1993
Canadian High Arctic (e.g. Axel Heiberg, Ellesmere, Prince of Wales, Somerset, Devon, Cornwallis Islands)	Curtis, 1975; Hunter and Leach, 1983; Thomson *et al*., 1986; Dale *et al*., 1989; Carey, 1991; Aitken and Gilbert, 1996; Conlan *et al*., 1998.

2.2 Ecology and Zoogeography of Modern Arctic Marine Molluscs

2.2.1 Zoogeography

Early in the history of marine benthic community studies, the concept of "parallel communities" proposed by Thorson (1957) played a prominent role in our understanding of benthic community structure. Thorson stated that "parallel communities" inhabit the same type of bottom at similar depths and are characterized by different species of the same genera which replace each other across broad regions of the seafloor. For example, the Arctic *Macoma* community defined by Thorson (1957) is widespread in shallow water at depths less than 50 m on mixed bottoms, and the *Astarte crenata* community dominates deep water at depths greater than 50 m on the continental shelf associated with muddy substrates. The *Portlandia arctica* community described by Thorson (1957) and Ockelmann (1958) from east Greenland inhabits soft muddy bottoms at depths from 10 to 60 m. A similar association described by Ellis (1960) from Baffin Island inhabits soft mud at a depth of 22 m (Table 2.2).

The concept of parallel communities has been gradually replaced by other concepts of community structure such as "gradient analysis", which examines the association between taxa and particular environmental variables (Mills, 1969; Syvitski *et al.*, 1989). Dale *et al*. (1989) examined benthic community structure in relation to the composition of bottom sediments within Baffin Island fjords. Benthic communities inhabit different types of substrates described as soupground, softground, firmground, and hardground. Soupground substrates with high water contents are associated with fjord-head environments characterized by rapid sedimentation.

Table 2.2 Benthic invertebrate associations present in East Greenland fjords and on the continental shelf in north Baffin Island.

Locality:	East Greenland fjords	Baffin Island fjords	McBeth Fjord, Cambridge Fjord, and Itirbilung Fjord
Source:	Thorson, 1957; Ockelmann, 1958	Ellis, 1960	Syvitski *et al*., 1989; Aitken, 1990
1.	***Portlandia arctica* community**		
	Portlandia arctica	*Portlandia arctica*	*Macoma calcarea* *Musculus discors* *Mya truncata* *Hiatella arctica* *Portlandia arctica*
Depth (m):	10-15 to 50-60	22	5-40
Substrate:	Soft mud	Mud	Sandy mud
2.	**Arctic *Macoma* community**		
	Astarte borealis *Astarte elliptica* *Astarte montagui* *Axinopsis orbiculata* *Clinocardium ciliatum* *Macoma calcarea* *Macoma moesta* *Mya truncata* *Nucula tenuis* *Nuculana pernula* *Ophiocten sericeum* *Serripes groenlandicus* *Thyasira gouldi*	*Astarte borealis* *Astarte montagui* *Axinopsis orbiculata* *Macoma calcarea* *Macoma moesta* *Mya truncata* *Nucula tenuis* *Serripes groenlandicum* *Thyasira* sp.	*Axinopsis orbiculata* *Macoma calcarea* *Mucula belloti* *Yoldiella lenticula* *Yoldiella intermedia*
Depth (m):	4 to 50-60	5-50	100-560
Substrate:	Mixed; sandy clay	Sandy mud	Sandy mud, gravel
3.	***Astarte crenata* community**		
	Astarte crenata *Cuspidaria glacialis* *Cuspidaria subtorta* *Ctenodiscus crispatus* *Delectopecten greenlandicus* *Nucula tenuis* *Ophiopleura borealis* *Portlandia intermedia* *Thyasira equalis* *Yoldiella frigida*	*Astarte crenata* *Nucula tenuis* *Portlandia* spp. *Thyasira* spp.	*Astarte crenata* *Bathyarca orbiculata* *Axinopsis orbiculata* *Yoldiella intermedia* *Yoldiella lenticula*
Depth (m):	30-40 to 550	50-500	255-750
Substrate:	Mud	Mud	Sandy mud

The *Portlandia* association (see Table 2.3) occurs in this environment. Benthic species with specific coarse grain-size requirements for tube construction (e.g. onuphid polychaetes) are reduced in number in these substrates. Softground substrates develop

where there is a reduction in the influx of clastic sediments to the marine environment. The *Maldanid* Association and *Onuphid* association (see Table 2.3) inhabit softground substrates (Dale *et al.*, 1989; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993). Firmground substrates are commonly found at the mouth of fjords in the sill area and at mid-fjord sill locations. The sills are composed of gravel ridges with cobbles, boulders and pockets of current-swept sand and gravel. These environments are characterized by low sedimentation rates and extensive erosion of the seafloor. Epifaunal organisms (see Table 2.3) such as *Musculus* sp. and *Buccinum* sp., dominate these coarse-grained substrates. Hardground substrates are represented by exposed bedrock surfaces at sills, the steep rocky sidewalls of the fjords, and isolated boulders on the seafloor. These rocky surfaces are often completely coated with encrusting organisms such as sea anemones, serpulid polychaetes, and encrusting bryozoans (Dale *et al.*, 1989).

Syvitski *et al*. (1989) analyzed the gradients in the organic carbon content of seafloor sediments within Cambridge Fiord, Baffin Island (Figure 2.1). Organic carbon increases seaward in inner fjord basins reflecting a decrease in the rate of clastic sedimentation away from the fjord-head river mouth, and decreases seaward in the main basin reflecting a seaward increase in the rate of clastic sedimentation associated with side-entry glaciers. They concluded that the organic carbon content of marine sediments could be used as a proxy indicator of sedimentation rates, which can influence the benthic community composition.

Table 2.3 Benthic molluscan associations from Baffin Island identified by Dale *et al*. (1989), Syvitski *et al*. (1989), Aitken and Fournier (1993).

	***Portlandia* association**	***Onuphid* association**	***Maldanid* association**
	Bivalvia *Axinopsis orbiculata* *Hiatella arctica* *Macoma calcarea* *Musculus discors* *Mya truncata* *Nucula belloti* *Portlandia arctica* *Thyasira gouldi* *Thracia* sp. Gastropoda *Cylichna* cf. *occulta* *Buccinum* sp.	Bivalvia *Astarte crenata* *Astarte striata* *Axinopsis orbiculata* *Bathyarca glacialis* *Chlamys islandica* *Cuspidaria glacialis* *Macoma calcarea* *Nucula belloti* *Portlandia arctica* *Yoldiella* spp. Gastropoda *Buccinum* sp. *Lepeta caeca*	Bivalvia *Astarte* spp. *Axinopsis orbiculata* *Bathyarca glacialis* *Cuspidaria glacialis* *Macoma calcarea* *Nucula belloti* Gastropoda *Buccinum* spp. *Lepeta caeca* *Natica clausa*
Depth (m):	5-40	50-300	40-700
Substrate:	Soupground: underconsolidated mud and sand	Softground: mud, sand, gravel	Softground: muddy sand
Water mass:	Seasonally variable, shallow surface water	Arctic waters	Atlantic waters
Temperature:	0-8 °C	-1.8-1.8 °C	0-2.0 °C
Salinity:	20-30 ‰	< 30.0-34.5 ‰	34.2-35 ‰

Deposit feeders (e.g. *Portlandia arctica*) can survive environments characterized with low organic carbon content and high sedimentation rate; whereas suspension feeders (e.g. *Hiatella arctica*, *Mya truncata*, *Astarte borealis*) are commonly associated with high organic carbon content and low sedimentation rate. These authors also noted that water temperature influences the distribution of molluscs. For example, the abundance of *Portlandia arctica* increased toward the limits of its depth range, where the temperature decreased to -1.0°C, and the distribution of this species appears to be correlated with the depth of the summer thermocline (Figure 2.2).

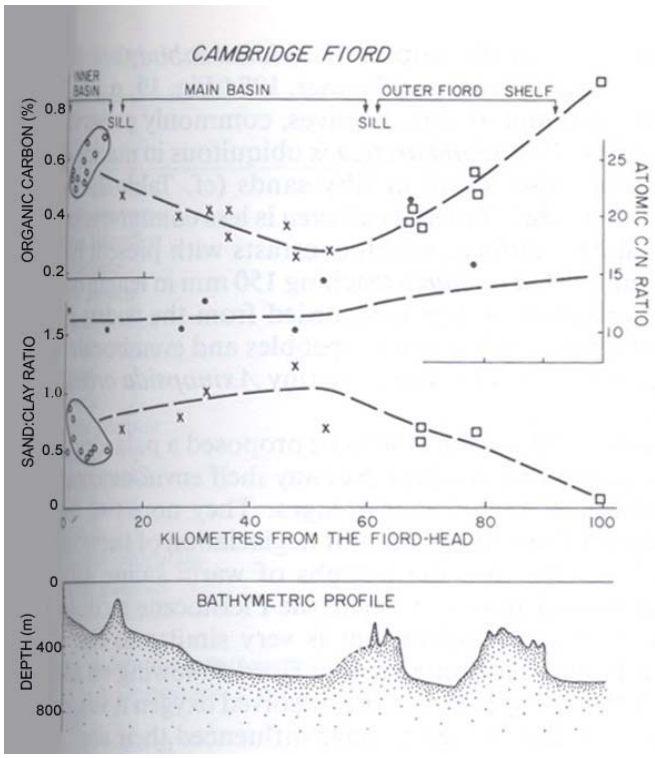


Figure 2.1 Gradients in organic carbon content and sand:clay ratios in seafloor sediments from Cambridge Fiord (Adopted from Syvitski *et al*., 1989).

Much of the published literature on arctic marine benthos has focused on describing geographic variations in the composition and abundance of the benthic fauna and determining benthic biomass under various environmental conditions (Curtis, 1975; Thomson, 1982; Stewart *et al.*, 1985; Thomson *et al.*, 1986). Common arctic macrobenthic communities inhabiting shallow-water and deep-water environments both in fjords and on the continental shelf are described in Table 2.4.

2.2.2 Ecology

2.2.2.1 Life Habits

Little is known of the life habits of modern arctic marine molluscs because of the environmental limitations that constrain research efforts in high latitude marine

environments. On the other hand, knowledge on life habits, especially the mode of feeding and locomotion, play a critical role in the paleoecological reconstruction of fossil mollusc associations. Thorson (1950) was among the first marine biologists to analyze ecological patterns in the life cycles of marine benthos. He noted that species in the shallow coastal waters of warm seas tended to have pelagic larvae but non-pelagic larvae became increasingly predominant at greater depths and in the colder northern seas. This phenomenon was defined as "Thorson's Rule" and represents a fundamental concept in benthic ecology (Mileykovsky, 1971, 1972).

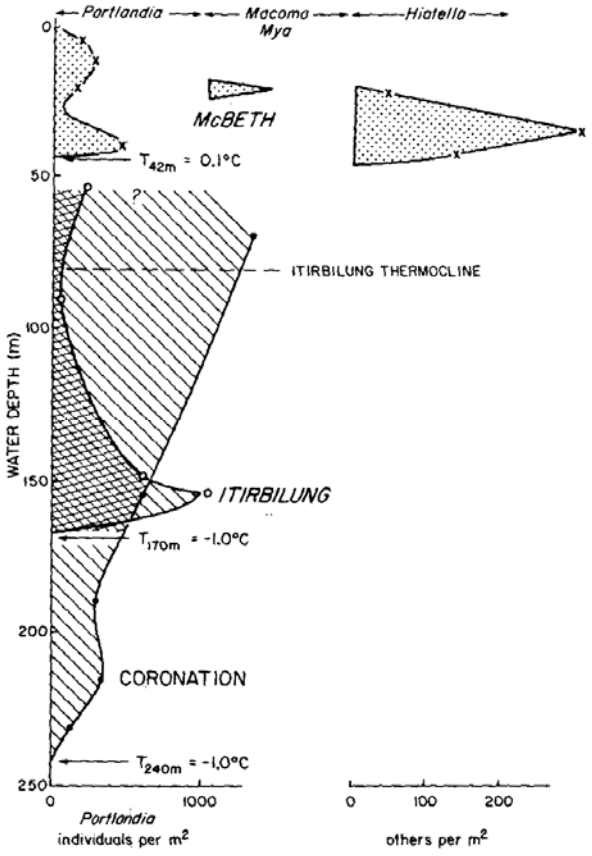


Figure 2.2 Environmental gradients and the abundance of bivalves as a function of depth within the *Portlandia* Association of Baffin Island fjords (Adopted from Syvitski *et al*., 1989)

Table 2.4 Common molluscs occurring in different marine environments

Environments	Shallow water near glacier margins and deltas in fjords	Deep water in fjords	Shallow nearshore marine environments on the continental shelf (including intertidal flats)	Deep water marine environments on the continental shelf
Common Species in Community	Gastropods *Buccinum hydrophanum,* Bivalves *Astarte borealis* *Axinopsida orbiculata* *Chlamys islandica* *Hiatella arctica* *Macoma calcarea* *Musculus discors* *Mya truncata* *Portlandia arctica* *Thyasira* sp.	Bivalves *Axinopsida orbiculata* *Chlamys islandica* *Hiatella arctica* *Nucula belloti* *Nuculana pernula* *Portlandia arctica* *Yoldiella intermedia* *Yoldiella lenticula*	Gastropods *Cylichna alba* *Oenopota bicarinata* *Littorina saxatilis* Bivalves *Astarte borealis* *Astarte montagui* *Hiatella arctica* *Macoma calcare* *Mya truncata* *Mytilus edulis* *Serripes groenlandicus* *Thyasira* sp	Gastropods *Buccinum* spp. Bivalves *Astarte crenata* *Astarte borealis* *Astarte montagui* *Axinopsida orbiculata* *Macoma calcarea* *Nucula belloti* *Yoldiella* sp.
Depth	0- 50m	>50m	0-50m	>50m
Substrates	Underconsolidated mud and sand	Poorly sorted mixtures of mud, sand, gravel	Sandy mud to mud	Mud
Sources	Dale *et al*., 1989; Syvitski *et al*., 1989	Dale *et al*., 1989 Aitken and Fournier, 1993	Dale *et al*., 1989; Syvitski *et al*., 1989	Dale *et al*., 1989; Thomson, 1982.

Locomotion habits of marine organisms are determined by different feeding modes and the nature of substrate (Stanley, 1970). Descriptions of locomotion habits of benthic molluscs appear in the community studies published by Stewart *et al*. (1985), Dale *et al*. (1989), Peacock (1989), Syvitski *et al*. (1989), Schmid and Piepenburg (1993), Dyke *et al*. (1996a), and Gordillo and Aitken (2000). Stanley (1970) studied the habit and mode of locomotion of molluscs in detail and classified bivalves into seven major categories according to the mode of locomotion: byssally attached, cemented, reclining, swimming, burrowing, boring, and nestling. In most recent studies, mollusc species are commonly described as suspension feeders, deposit feeders, browsers, and carnivores in regard to

different feeding habits. Deposit feeders (e.g. *Portlandia* sp.) acquire their nutrition from the sediments they inhabit, whereas suspension feeders (e.g. *Mya* sp.) collect food particles suspended above sediments (Stanley, 1970; Yonge and Thompson, 1976). Browsers (e.g. limpets and top shells) encrust vegetation from the surface of substrates where they attach to. Carnivores feed on dead or declining as well as active prey. They can poison and seize active prey as large as, or even larger than the predator (Yonge and Thompson, 1976).

2.2.2.2 Environmental Variables

Sea water properties, in particular temperature and salinity, affect invertebrate populations, and the movement of water masses contributes to the dispersal of species, chiefly of those having planktonic larval stages (Thorson, 1950). Three major water masses that influence the distribution of marine molluscs in arctic and sub-arctic regions have been described in detail by Bailey (1957) (see Table 2.3, Figure 2.3). The *Portlandia* association dominates at depths of 5 to 40 m associated with seasonally variable, shallow surface waters (0 to 8°C, 20-30‰) which develop in July and August from the mixing of Baffin Island Current water with fresh water from rivers and melting sea ice. This surface water mass occurs in fjords at depths of 5 to 60 m and at 50 to 100 m across the continental shelf (Aitken and Fouriner, 1993). Thomson (1982) identified a benthic association characterized by the bivalves *Astarte borealis* and *Macoma moesta*, and various polychaete species associated with silt and sand substrates in this water mass in the eastern Canadian Arctic.

The cold arctic water mass (-1.8 to 1.8°C, <30.0 to 34.5‰) originates in the Arctic Ocean and enters Baffin Bay via Smith Sound, Jones Sound and Lancaster Sound where

it flows at depths of 100 to 300 m on continental shelf. The *Onuphid* Association described by Syvitski *et al*. (1989) occurs under the influence of this water mass in eastern Baffin Island fjords. A benthic association characterized by the bivalves *Macoma calcarea* and *Astarte montagui*, and the ophiuroid *Ophiura robusta* was observed by Thomson (1982) within this water mass representing a transition zone between the surface arctic water and deeper Atlantic water masses (50 to 250 m) on the continental shelf in the eastern Canadian Arctic.

The West Greenland Current, a relatively warm, saline water mass originating in the North Atlantic Ocean, is advected north via Davis Strait into Baffin Bay. This current mixes with Baffin Island Current water on the continental shelf at depths of 300 to 1300 m, becoming colder (0 to 2°C, 34.2 to 35‰). The Maldanid Association in eastern Baffin Island fjords and on the continental shelf has developed in association with this water mass (Syvitski *et al.*, 1989; Aitken and Fouriner, 1993). A benthic association identified by Thomson (1982) and dominated by the bivalve *Bathyarca raridentata*, the polychaetes *Praxillella gracilis*, *Samythella* sp.nr.*neglecta*, and *Thelepus cincinatus*, and various ophiuroid species occurs associated with this water mass at the depths of 250 to 1000 m in the eastern Canadian Arctic.

In arctic and sub-arctic regions, sea ice represents a significant environmental factor influencing the structure of the marine benthos. Ice-rafted cobbles commonly support epifaunal organisms as "faunal islands" on the seafloor (Dale *et al.*, 1989). The faunal islands can occur in areas of otherwise unsuitable substrates, particularly in glaciomarine environments, with significant implications for the dispersal of benthic fauna over the seafloor. The annual growth and decay of sea ice, in combination with

prolonged summer insolation and terrestrial runoff, modifies surface water temperatures and salinities and may result in mortality from physiological stress (Dale *et al.*, 1989).

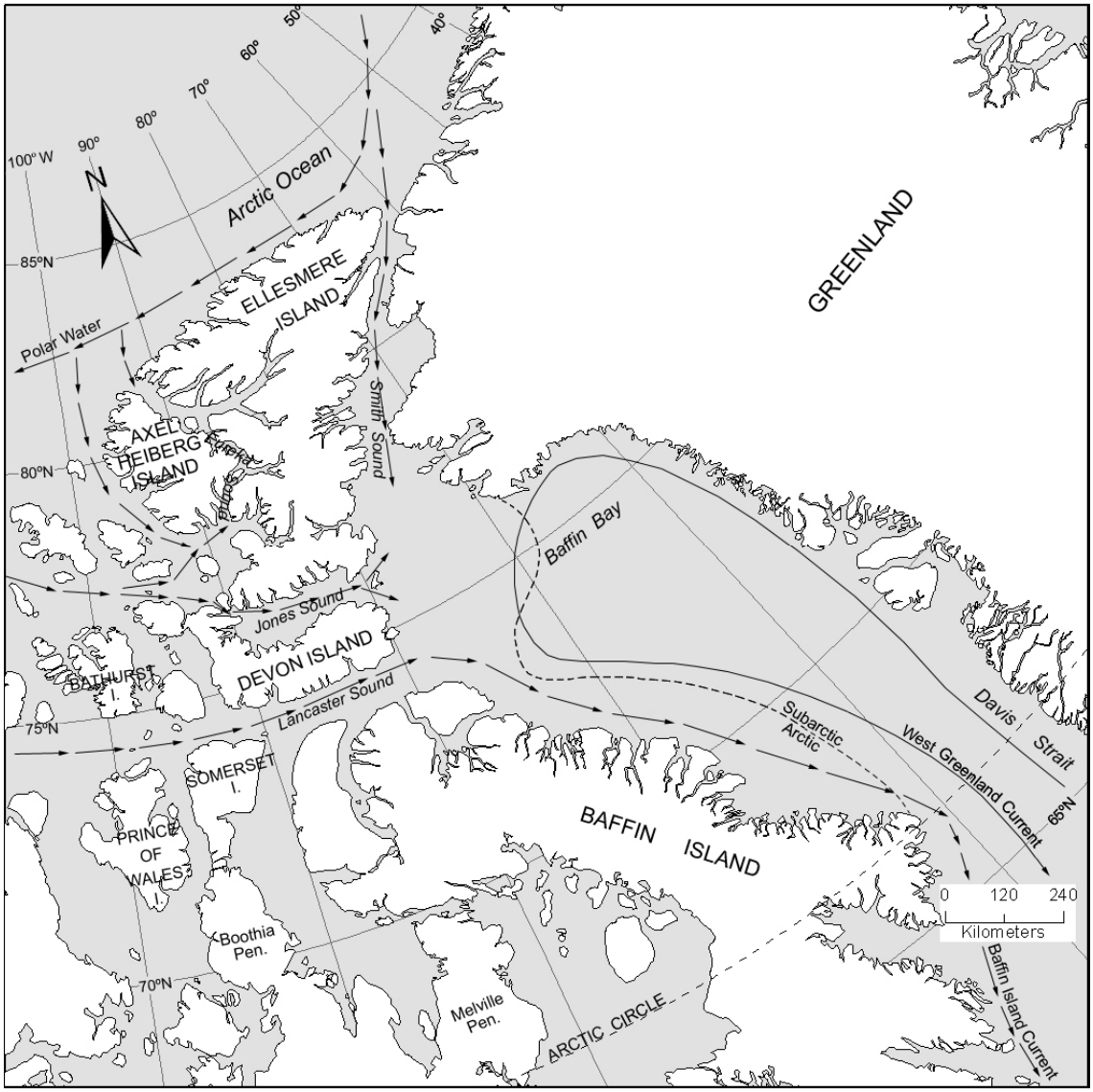


Figure 2.3 Ocean surface currents around the Canadian Arctic Archipelago. Adopted from Barry (1993) and Aitken and Gilbert (1996).

In most of the High Arctic, a stable, brackish layer forms at the ocean surface with temperatures occasionally greater than 5°C and salinities less than 20‰. An almost

barren zone is kept clear of life at depths from 0 to 3 meters associated with the occurrence of this "fjord water" mass (Thorson, 1933, 1934; Aitken and Gilbert, 1996). The presence of sea ice in the high arctic shortens the period of primary production and restricts the euphotic zone to shallow depths (30-50 meters) therefore limiting the food resources available to the benthos (Ellis, 1960). Many marine species only mature and spawn within a restricted range of temperatures that is significantly influenced by variations in sea ice cover (Lemche, 1941a, b). Nearshore marine sediments and the associated benthic organisms can be frozen into sea ice by the process of suspension freezing. Suspension freezing occurs in open and shallow water during a freezing storm and following the supercooling of the water column (Reimnitz *et al.*, 1992). Sediments and biota frozen into sea ice can be transported seawards, thus contributing to mortality of a shallow-water macrofauna in the Canadian High Arctic (Reimnitz *et al.*, 1992).

Ice scouring by grounding drift ice and pressure ridges is a major chronic disturbance to both the shore and seafloor in polar regions. Icebergs have been known to scour a swath of seabed as wide as 1375 m and gouge an incision as deep as 11.5m (Lewis and Blasco, 1990). Gutt *et al*. (1996) found that the first immigrants into deep sea ice scours were organisms such as fish, echinoderms, and mobile bivalves. Conlan *et al*. (1998) studied ice scour disturbance to benthic communities in the Canadian High Arctic, and noted that ice scouring appeared to favor deposit-feeding and scavenging taxa, for example, buccinid gastropods and lysianassid amphipods. They found ice scouring eliminated or damaged large organisms such as kelp, sea urchins, and bivalves. As a result, suspension feeders and predators were more abundant in deeper water where scouring was less evident. These authors also observed that the ice scour

communities closely resembled the inshore, shallow water benthos inhabiting the seafloor outside of ice scours, in spite of the 300 to 400 m separation of the scours from the inshore area, differences in water depth (the scours were 3 to 12 m deeper), and differences in kelp cover (the scour lacked kelp cover, while the inshore samples had nearly 100% kelp cover). They stated that ice scour disturbance is a major factor in defining inshore community structure, and that depth-related faunal transitions along ice-scoured coastlines may well predict the course of succession in offshore ice scours.

2.3 Paleoenvironmental Research

Paleoecology is the study of the relationship of ancient organisms to their natural environment, and how these organisms functioned within their habitat and toward each other (Cooper, 1988; Pickerill and Brenchley, 1991). Taphonomy is the "science of the laws of burial" (Efremov, 1940) and typically involves the recognition of both information loss (e.g. the decay of soft parts, transportation and fragmentation of shell materials, and secondary post-burial processes) and information gain (e.g. evidence about the depositional environment) (Pickerill and Brenchley, 1991). With respect to taphonomy, the terms "autochthonous", "parautochthonous", and "allochthonous" are used to describe the nature of fossil preservation. If the preserved bodies are recorded *in situ* and therefore record the environment in which they lived, they are autochtonous assemblages; if they are transported (e.g., bear evidence of shell abrasion and/or fracturing, selective loss of size classes) and therefore indicative of the environments in which they finally accumulated, they are allochthonous assemblages; if they reflect a situation between these two extremes, they are parautochthonous assemblages representing essentially *in situ*, but locally reworked faunas (Kidwell, 1986; Pickerill

and Brenchley, 1991). It is only under exceptional conditions that *in situ* faunas are preserved within siliciclastic sediments, and most have been transported and mixed to different degrees by sedimentological and biological processes. The evaluation of the degree of transportation and mixing of the macrobenthos is important and must be undertaken in any paleoecological analysis.

2.3.1 Taphonomic properties

The length of time a shell remains at the surface and the time it spends buried just below the surface in the taphonomically active zone (TAZ) are significant factors in determining whether the shell will become part of the preserved fossil assemblage (Parsons-Hubbard *et al.*, 1999). The TAZ was defined by Aller (1982) as an undersaturated zone near the sediment-water interface where pore waters are undersaturated with respect to both aragonite and calcite and most dissolution of carbonate minerals occurs. Periodic exhumation causes continued destruction of shells with the longest-surviving shells being those that are less-frequently exposed at the surface. While exposed at the sediment/water interface or shallowly buried in the TAZ, shells undergo the most degradation. A shell's history of burial and exhumation is the primary determining factor of its taphonomic conditions in the TAZ. The exposure history of the shell is far more important than its age.

The nature of a fossil concentration can be defined by a range of preservational features, as suggested by Pickerill and Brenchley (1991), the most important of which are: 1) the orientation of fossils, including life orientation; 2) the relative degree of articulation; 3) the degree of fragmentation; 4) the proportion of different elements of a skeleton, for example, the left or right valves of bivalves; 5) the convex-up to convex-

down ratio of shells; 6) the degree of abrasion, corrosion or bioerosion of skeletons; 7) the type of shell fillings or coatings; 8) evidence for early dissolution of skeletons and 9) any unusual features of preservation.

The study of taphonomic processes allows death assemblages to be interpreted by observing the shell remains in the context of physical and biological processes.

Encrustation is a good indicator of the duration of exposure of shells at the sediment-water interface (Parsons and Brett, 1991). Most hard parts are encrusted after death. In general, the degree of encrustation is controlled by an interaction between energy and exposure (Parsons and Brett, 1991). Encrustation occurs more frequently to shells in low-energy environments than in high-energy environments (Meldahl and Flessa, 1990). It is difficult for epifaunal organisms to settle on shells which are frequently buried and exhumed in high energy environments (e.g., shallow subtidal and lower intertidal settings). Furthermore, high rates of abrasion quickly wear epibionts off the shells in high energy environments.

Fragmentation serves as a proxy of environmental energy. The degree of shell fragmentation tends to be highest in environments with high water turbulence and coarse substrates such as beaches, tidal channels, and reef crests (Parsons and Brett, 1991). Furthermore, shells can be damaged and fragmented by drift ice in intertidal and shallow subtidal environments where ice scouring is active.

Abrasion of shells occurs when they are exposed to moving particles or when the shells themselves are moved relative to other particles. The most common effect of abrasive action on mollusc shells is the loss of surface ornamentation. Intense abrasion reflects high-energy settings (nearshore waves, currents or tidal action) (Parsons and

Brett, 1991). Driscoll and Weltin (1973) demonstrated that shells with a large surface area per unit weight are more vulnerable to abrasion than those with smaller surface areas per unit weight, and environments characterized by coarse substrates cause faster and more intense abrasion than in other environments (Driscoll and Weltin, 1973).

Dissolution usually appears as general pitting and corrosion on shell surfaces. Different skeletons display different solubility in acidic solutions. Calcitic hard parts with a high magnesium carbonate content (common in echinoderms) are the most soluble, followed in descending order by aragonitic (many molluscs) and low magnesium calcitic hard parts (e.g., oysters and brachiopods) (Flessa and Brown, 1983). Chemical dissolution causes mollusc shells (aragonitic hard parts) to lose their colour and luster first, and then become chalky.

Brett and Baird (1986) introduced the term *corrasion* to describe the general degradation of skeletal surfaces when it is too difficult or time-consuming to attempt to separate out the many possible contributors to dissolution, corrosion, and abrasion. This term is useful for fossil specimens where it is difficult to distinguish between abrasion and corrosion but general surface degradation can still be recognized to reflect the overall condition of preservation (Parsons and Brett, 1991).

Bioerosion is the result of a search for food by grazers and predatory organisms, and for shelter (Parsons and Brett, 1991). Many grazers (e.g., gastropods, sea urchins, polychaetes, etc.) grind away the surface of shells in search of algae, erasing evidence of previous bioerosion and other taphonomic features, and often leave no recognizable traces. Boring sponges (family Clionidae) are destructive agents on molluscs, barnacles and other carbonate skeletons (Neumann, 1966). On a smaller scale, algae can bore into

carbonate skeletons and degrade the outer surface of mollusc shells creating a fine-grained material (micrite) that may surround fossil shells. The presence of boring algae indicates that the shell was exposed to light at the sediment-water interface prior to final burial (Parsons and Brett, 1991). A scanning electron microscope is required to properly identify algal borings and distinguish them from fungal borings which do not require light for growth (Perkins and Tsentas, 1976). Bioerosion can produce distinct biogenic structures (trace fossils) that facilitate the recognition of non-preservable organisms in fossil shell assemblages (Frey, 1975).

Articulation of multi-element skeletons is a valuable feature that indicates the time of exposure since death and/or the energy of the depositional environment. Bivalves tend to disarticulate under high-energy conditions, however, rapid burial can preserve significant numbers of articulated shells even in high-energy settings (Parsons and Brett, 1991). The two valves often display different hydrodynamic properties and are transported separately. For example, Frey and Henderson (1987) examined the distribution of left and right valves of *Donax variabilis* in a barrier island environment and observed that valves were moved preferentially by nearshore currents so that the right valves were found predominantly in the longshore channel, and left valves predominantly inside the tidal inlet. Therefore, a significant concentration of one valve type implies environments with dynamic hydrodynamic properties, such as beaches or areas with tidal influence (Frey and Henderson, 1987).

Orientation refers to the alignment of shells within or on sediments and can reflect the life position of the organism or it can be the result of post-mortem reorientation of shells by fluid flow or biological reworking (Parsons and Brett, 1991). Mollusc shells

generally orientate with the long-axis parallel to current directions and perpendicular to waves (Nagle, 1967). Concave-down positions of bivalve shells are often associated with strong currents and waves (Clifton and Boggs, 1970), while concave-up positions usually imply low energy environments (Emery, 1968), probably because shells in concave-down positions are more stable on the seafloor than shells in concave-up positions. Shell orientation can be an important tool for reconstructing the energy of currents and waves of ancient environments, but only the last current direction prior to burial is recorded, which may or may not be indicative of the average current direction (Parsons and Brett, 1991). Recognizing shells in life position always points to rapid burial.

Sorting involves a systematic segregation of fossil elements and is recognized in two ways: size and shape segregation (Speyer and Brett, 1988a). Shape-sorted associations imply differences in hydrodynamic properties, independent of particle size (Lever, 1958). Size-sorting can demonstrate the pattern of the energy gradients in aquatic environments through the preservation of size-sorted shell assemblages. Left-right sorting of bivalve shells often reflects prolonged exposure to oscillatory wave-generated currents or minor transport in nearshore environments (Speyer and Brett, 1988a). Accumulations of similar-sized small fossils implies selective winnowing and transport of shells by currents in high energy settings, with evidence of fragmentation, the shape of shells or other features indicative of transport (Speyer and Brett, 1988a).

2.3.2 Comparable Taphonomy and Taphofacies

The taphonomic history of shell assemblages is strongly correlated to environmental settings and sedimentary conditions, and is reflected in distinctive taphonomic

properties. Taxa display different manners of preservation between beds and different taxa show various manners of preservation within the same bed. Speyer and Brett (1988b) provide a basis for comparing taphonomic properties between beds by defining taphonomic properties, devising indices for these properties, and quantifying the various modes for each of them. These authors proposed the term "taphofacies" to define bodies of rock distinguished from other vertically and laterally related bodies of rock on the basis of their particular suite of taphonomic properties (Speyer and Brett, 1988a). The taphofacies models constructed in their study described the distribution of taphonomic features that are obviously the products of specific environmental conditions. There are seven taphofacies constructed on the basis of the distribution of taphonomic properties as illustrated in Figure 2.3. Sedimentation rate, turbulence, and oxygenation level were incorporated into the taphofacies model to describe the variations in sediment supply, environmental energy, and surface exposure involved in the process of biostratinomy. The duration of surface exposure is significant and influences the relative effects of all other destructive agents. As exposure time decreases the degree to which currents and surface processes may fragment, disarticulate, reorient, sort, or abrade and corrode skeletal remains is correspondingly restricted (Speyer and Brett, 1988a).

The objective of constructing taphofacies is to maximize the amount and quality of information offered by the skeletonized remains of past life. The theoretical mosaic of taphofacies presented in Figure 2.4 is based firstly, on deductive logic (i.e., fragmentation is greatest where water energy and exposure time are maximized), and secondly, detailed field studies and empirical taphonomic data (Speyer and Brett, 1988a). The utility of such models lies in their ability to predict spatial and temporal

stratigraphic relationships. Studying comparative taphonomy and taphofacies models allow us to understand the nature of sedimentation events and the distribution of physical-chemical conditions across a variety of environments. The mosaic of taphofacies provides a model and a framework for reconstructing paleoenvironments and understanding paleoecological phenomena.

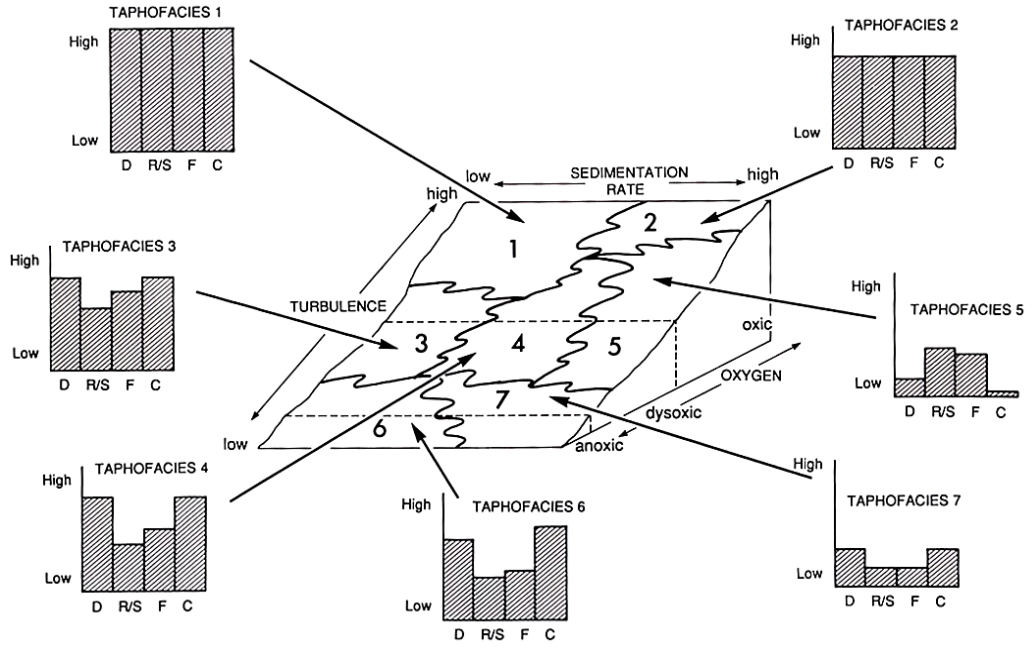


Figure 2.4 Generalized taphofacies recognized from Paleozoic continental shelf sequences, where seven distinct taphofacies are differentiated on the basis of shell disarticulation. (D), reorientation and sorting (R/S), fragmentation (F), and corrosion = corrosion/abrasion (C). Generalized environmental conditions of individual taphofacies, as reflected by the parameters of sedimentation rate, turbulence and oxygenation, are indicated accordingly (Adopted from Pickerill and Brenchley, 1991).

2.3.3 Paleo-communities and Death Assemblages

A paleo-community refers to an assemblage of organisms inferred to represent a distinct biological entity and normally related to a specific [paleo] environment (Pickerill and Brenchley, 1991). The remains of skeletonized organisms commonly represent a paleo-community because soft-bodied components are generally not

preserved in the fossil record. Biogenic structures (trace fossils), as a secondary expression of ancient life, are preserved in numerous places where body fossils are not, and they document behavioral and ecological traits produced by species in a paleo-community (Frey, 1975). Such faunal groupings have been referred to as assemblages rather than communities in both the fossil record and recent environments.

Some recent studies focusing on the palimpsests of death assemblages provide evidence of the reliability of biological information preserved in the fossil record (e.g. Kidwell, 2001, 2002). Sedimentary death assemblages consistently contain more species than are sampled in any single census of the local living community (Kidwell, 2002). Although this excess dead-species richness can result in part from postmortem delivery of exotic species from other environments, most reports have argued that many (or most) "dead only" species were actually indigenous to the local community, but simply had living populations that were too sparsely distributed, patchy, or ephemeral to have been encountered during sampling. A death assemblage is not biologically equivalent to a census of a living community, but sums dead-shell input (minus shell destruction) over some longer period, permitting accrual of a time-averaged species richness (Kidwell, 2002). Kidwell (2001) examined the preservation of species abundance in marine death assemblages and noted that species that are dominant in a single live census also dominate the local death assemblage, and species that are rare or unsampled alive are also rare in death assemblages. The fossil record, therefore, largely portrays the modern faunas from which it is derived.

2.3.4 Guild Analysis

Guild structure has been used to describe community and assemblage structure in ecology and paleoecology (Scott, 1978; Ausich and Bottjer, 1982; Bambach, 1983; Dauer, 1984; Staff and Powell, 1999). Root (1967) defined a guild as "a group of species that exploit the same class of environmental resources in a similar way. This term groups together species, without regard to taxonomic position, that overlap significantly in their niche requirements" (Root, 1967: p. 335). In this study, we adopt the terminology of Staff and Powell (1999) and recognize three general factors when assigning species to specific guilds: 1) food source (food source and feeding type), 2) space utilization (life positions and life habits), and 3) bauplan (intrinsic features). The purpose of guild analysis is to examine the habitat structure of a community as it functioned in some place at some time. Guild analysis reveals both the nature and the style of ecospace utilization by the community and the amount of ecospace utilized by the community (Bambach, 1983). Table 2.5 shows examples of guilds for Bivalvia and Gastropoda.

2.3.5 Preservation Pattern

The preservation potential of high latitude marine molluscs has been studied by several authors (e.g., Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000, 2001). Bivalves and gastropods possess the best preservation potential. In subarctic and arctic marine environments the macrofauna inhabiting nearshore environments exhibit the greatest preservation potential among modern marine invertebrates (Curtis, 1975; Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000). The guild composition of the potentially preservable macrofauna differs from that in the modern macrofauna:

infaunal suspension feeders and epifaunal browsers exhibit the greatest preservation potential (Aitken, 1990). These preservation biases have been reflected in many Quaternary macrofaunal assemblages and have been studied to test if the fossil record is adequate to reconstruct paleoenvironments (Curtis, 1975; Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000).

Table 2.5 Examples of guilds for Bivalvia and Gastropoda: taxa corresponding to specific guilds recorded in the fossil assemblages examined for this study appear in brackets (Adopted from Bambach, 1983).

Gastropoda	Cap-shaped grazers (limpets) Spired grazers (e.g. *Margarites*) Epifaunal predators (e.g. *Buccinum*, *Colus*, *Oenopota*, *Cylichna*) Tiny, interstitial infaunal suspension-feeders High-spired infaunal predators Low-predators Epifaunal suspension-feeder (e.g. *Trichotropis*)
Bivalvia	Nonsiphonate shallow infaunal suspension feeder Siphonate shallow infaunal suspension-feeder (e.g. *Astarte*, *Clinocardium*, *Serripes*, *Thracia*, *Pandora*) Sluggish siphonate deep infaunal suspension-feeder (e.g. *Mya*) Rapid siphonate deep infaunal suspension-feeder Deep infaunal mucus-tube suspension-feeder Nonsiphonate deposit-feeder Siphonate surface deposit-/suspension-feeder (e.g. *Macoma*) Siphonate palp-probiscide deposit-feeder (e.g. *Nucula*, *Nuculana*, *Portlandia*, *Thyasira*) Endobyssate (semi-infaunal) suspension-feeder (e.g. *Hiatella*, *Lyonsia*) Erect epibyssate suspension-feeder Reclining epibyssate suspension-feeder (e.g. *Musculus*) Free-lying epifaunal suspension-feeder (e.g. Delectopecten) Swimming epifaunal suspension-feeder Cemented epifaunal suspension-feeder

Infaunal suspension-feeding bivalves such as *Hiatella arctica*, *Mya truncata* and *Astarte* sp. have been observed to dominate both modern and fossil assemblages, and the infaunal deposit-feeder *Portlandia arctica* dominates the early deglacial fossil record. It is critical to understand the ecology of these dominant bivalves that are significant in reconstructing paleoenvironments from fossil mollusc assemblages (Dyke

et al., 1996a; Gordillo and Aitken, 2000, 2001). For example, *Hiatella arctica* disperses via planktotrophic larvae, the development of which depends on access to a pool of organic matter derived in large measure from marine phytoplankton. Since biochemical processes such as the photosynthesis of marine phytoplankton are reliant on the quality and quantity of available light in shallow marine environments, this species should be restricted to shallow water environments because the food source is sensitive to environmental fluctuation.

2.3.6 Holocene Paleoenvironments and Faunal Succession

The nature of environmental change throughout the Holocene is described in Chapter 1.3.1. During the initial stage of the last deglaciation of the Canadian Arctic, *Portlandia arctica* appears as the pioneer species in marine environments characterized by high rates of sedimentation (i.e. ice-proximal environments), occasionally associated with *Hiatella arctica* and *Mya truncata*. During the postglacial period, more species are observed, such as *Macoma calcarea* and *Axinopsida orbiculata*, with the unchanged dominance of the three species noted in the first phase of faunal succession. Modern marine environments, characterized by low rates of sedimentation, were established gradually in the latter stage of deglaciation. The addition of *Astarte borealis*, *Serripes groenlandicus*, *Clinocardium ciliatum*, and *Buccinum* sp. contribute to the presence of diverse molluscs assemblages during this period (Syvitski *et al*., 1989; Dyke *et al*., 1996a; Gordillo and Aitken, 2001; Table 2.6).

Table 2.6 Faunal successions during the Holocene in the Canadian Arctic Archipelago.

Period	Environmental conditions	Baffin Island fjords (from Syvitski *et al*., 1989)	Arctic Archipelago (from Dyke *et al*., 1996)	Prince of Wales, central Canadian arctic (from Gordillo and Aitken, 2001)
Deglaciation	Rapid retreat of marine ice margins throughout the regions. Large volumes of glacially derived melt-water were discharged into ice-proximal environments.	Pioneer *Portlandia* Association *Portlandia arctica*	*Hiatella arctica* association	*Hiatella arctica* *Mya truncata*
Early-mid Holocene	Considerable open water, reduced summer sea ice highest temperature during the Holocene, large volumes of summer meltwater. A climatic deterioration in mid-Holocene; ice shelves formed and large glaciers advanced.	Mature *Portlandia* Association *Portlandia arctica* *Hiatella arctica* *Mya truncata* *Macoma calcarea* *Axinopsida orbiculata*	↓ *Hiatella arctica - Mya truncata* association	+ *Macoma calcarea* *Portlandia arctica*
Late Holocene	100-400 a BP: the coldest period of the entire Holocene, more extensive sea ice, marked decline in temperature, glaciers advance to post-glacial maximum positions, expansion of landfast sea ice. Since 1925, a distinct increase in temperature; negative mass balances of glaciers and ice sheets, ice margins retreat, ice shelves are presently breaking up and melting.	Onuphid Association *Chlamys islandica* *Astarte montagui* *Astarte striata* *Astarte borealis* *Musculus* sp.	*Hiatella arctica* *Mya truncata* *Astarte borealis* *Macoma calcarea* *Serripes groenlandicus* *Clinocardium ciliatum*	+ *Astarte borealis* *Clinocardium ciliatum* *Serripes groenlandicus* *Buccinum* spp.

2.3.7 Paleoenvironmental Studies

Early research in mollusc paleoecology started with an implicit recognition of the importance of temperature, which is the basis of many paleoceanographic studies. Peacock (1989) stated that marine molluscs have an important part to play in late Quaternary paleoenvironmental studies and the strong association of certain taxa with

specific water masses in the oceans is a useful source of paleoenvironmental information. For example, Lemmen *et al*. (1994) noted that the faunal analysis of raised marine sediments could provide information about fjord depositional environments during the middle and late Holocene; a period for which there is limited paleoenvironmental information in the Canadian High Arctic.

Regional paleoenvironmental studies on arctic and sub-arctic marine benthos include works by Syvitski *et al*. (1989), Peacock (1989), Aitken (1990), Lemmen *et al*. (1994), Aitken and Bell (1998), Gordillo and Aitken (2000, 2001), and work by Dyke *et al*. (1996a) as part of the broad objectives of the *Paleogeographic Atlas of Glaciated North America Project* of the Geological Survey of Canada and *The Climate System History and Dynamics Project*. Among these studies, however, just a few were focused on the Canadian high arctic (Aitken, 1990; Aitken and Bell, 1998; Gordillo and Aitken, 2000, 2001); a situation that reflects to the problem of accessibility to high latitude research localities and the lack of commercial interest in this research field.

2.4 Problems and Gaps

Paleoenvironmental studies, especially studies on Quaternary marine environments in the arctic and sub-arctic regions, have been undertaken systematically in northwestern Europe, along the east coast of Baffin Island and west coast of Greenland, as well as in the Canadian high arctic over the last several decades (Mode, 1985; Thomsen and Vorren, 1986; Dyke *et al.*, 1996a; Simonarson *et al.*, 1998). However, there are still some critical high arctic regions where little or no systematic study has been undertaken, such as the Queen Elizabeth Islands. Glaciers or sea ice floating on the ocean's surface significantly influence the nearshore environments of this region. The

habitats of marine mollusc communities inhabiting this region have experienced variations in temperature, salinity and sea ice cover since the Last Glacial Maximum (LGM) (Stewart and England, 1983; Bradley, 1990; Hein and Mudie, 1991; Evans and England, 1992; Bourgeois *et al.*, 2000). In the Canadian high arctic, much more research is needed to obtain information relating to paleoecology of mollusc associations throughout the Holocene period.

CHAPTER 3 STUDY AREA AND THE PHYSICAL SETTING

3.1 Introduction

The study area is located in the regions of Mokka Fjord, Gibbs Fjord, and Eureka Sound in southeastern Axel Heiberg Island (Figure 3.1). Glaciers and sea ice have significantly influenced the fjords of southeastern Axel Heiberg throughout the Late Quaternary and Holocene periods. Most of Axel Heiberg Island and northern and west-central Ellesmere Island share the largest lake in the Queen Elizabeth Islands, the highest peaks of eastern North America, and one of the great fjord systems of the Canadian Arctic, the Greely Fjord system (Dawes and Christie, 1991).

Eureka Sound, 300 km long and 10-28 km wide, is the inter-island channel that separates Ellesmere and Axel Heiberg islands. Modern glaciers are limited to small, upland ice caps, but the region is bordered immediately to the east and west by extensive ice fields on central Axel Heiberg and Ellesmere islands.

3.2 Bedrock Geology and Physiography

Topographic relief in the study area and its relation to bedrock structure has been examined by Dunbar and Greenaway (1956), Bostock (1970), Thorsteinsson (1971), De Paor *et al*. (1989), Dawes and Christie (1991) and Trettin (1991). Mesozoic and early Tertiary clastic sedimentary rocks, consisting of alternating sandstone/siltstone and shale lithologies with minor igneous dykes, underlie the study area. The middle Eocene Eurekan orogeny resulted in folding and faulting of these sedimentary rocks developing the north-northwest trending ridges of the Joy Range immediately west of the study area. Maximum elevations in the Joy Range vary from 1000 to 1300 meters. Topographic relief declines southeastward from the highlands towards a narrow coastal plain

bordering Nansen Sound and Eureka Sound (Figure 3.2). The intervening hilly topography (maximum elevations vary from 400 to 550 meters) of the Eurekan Upland is dissected by glacially modified valleys and fjords: underfit streams presently occupy the valleys.

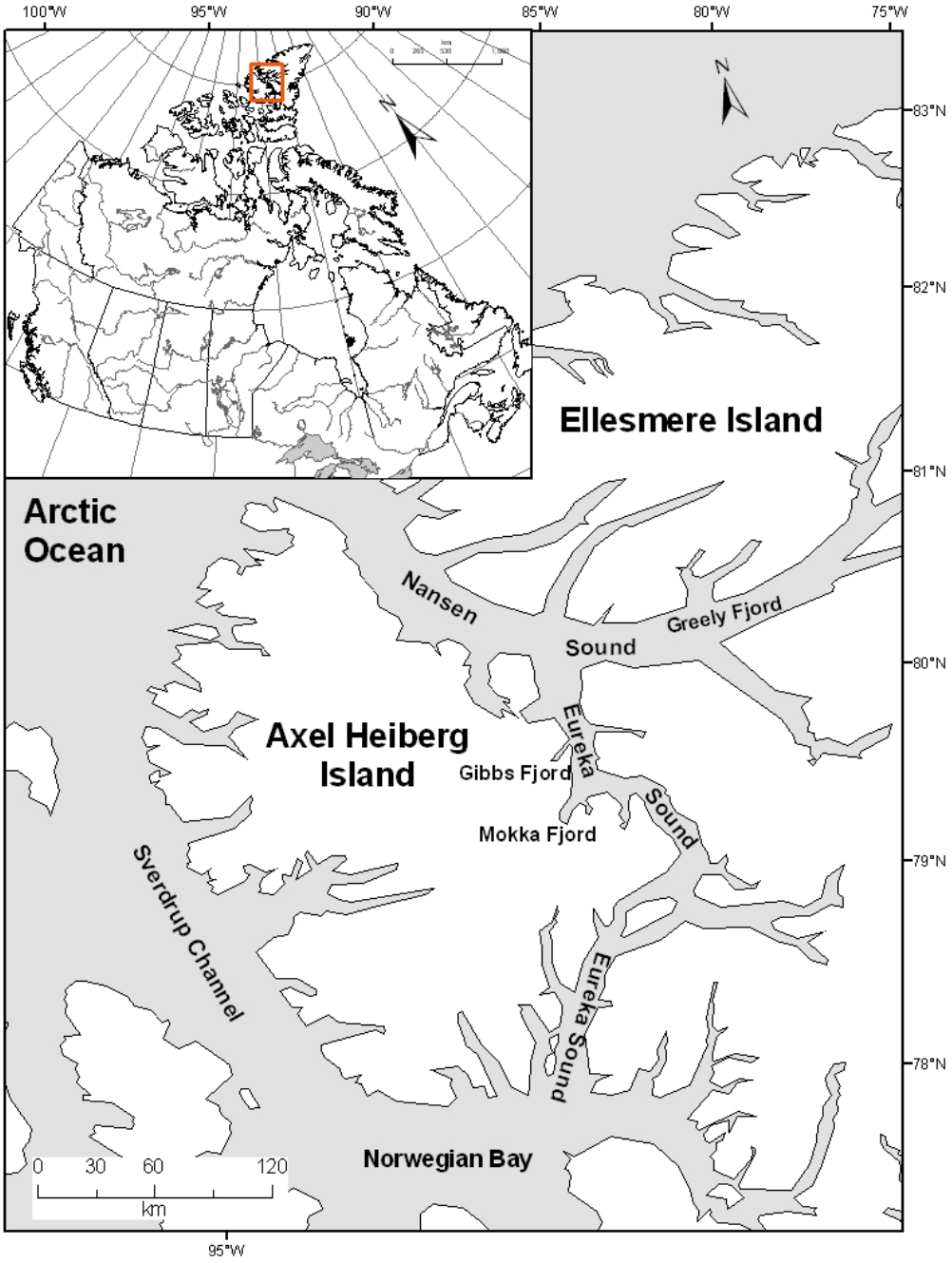


Figure 3.1 Map of the study area.

Figure 3.2 Photograph of the study area bordering Eureka Sound

3.3 Glacial and Post-glacial Geomorphology

Nansen Sound and Eureka Sound experienced extensive glaciation during the Late Wisconsinan (Bednarski, 1998; O'Cofaigh, 1999; England *et al.*, 2004). On the basis of recorded raised marine deltas, beaches and washing limits, and associated radiocarbon dates, Holocene marine limit reached a maximum elevation of ~150 meters above sea level (a.s.l.) along northern Eureka Sound and descends southwards to ~140 meters a.s.l. near the Sawtooth Mountains, with extensive deglaciation and marine transgression by 10.6 ka BP (Bell, 1996; Bednarski, 1998; O'Cofaigh, 1998, 1999). By 9.5 ka BP early Holocene regional deglaciation of the Fosheim Peninsula was underway and is characterized by a two-step retreat pattern. An initial rapid breakup of marine-based ice and extensive deglaciation by 9.2 ka BP is evidenced by the dating in two adjacent fjords on southwestern Ellesmere Island, the absence of ice marginal landforms and related marine

biofacies and the relative scarcity of raised marine sediments in the study area (Bell, 1996; O'Cofaigh, 1998). After this rapid retreat, a slower, terrestrial retreat occurred in the inner fjord and on the adjacent highlands with local ice caps persisting through the warmest period of the Holocene until 6-5 ka BP (Bell, 1996; O'Cofaigh, 1998). Reduced sea ice conditions and increased moisture availability probably benefited low-lying coastal icefields (Bell, 1996). "This two-step pattern confirms a distinct loading centre over Eureka Sound during the Last Glacial Maximum, and is compatible with independent glacial geological evidence indicating that the thickest ice was centred over the channel during the Late Wisconsinan" (O'Cofaigh, 1999: p.530).

3.4 Climate

The modern climate of the Queen Elizabeth Islands has been studied by Bradley and England (1978), Maxwell (1981) and Edlund and Alt (1989). Ground snow cover and airflow modify the temperature and precipitation regimes over the region. The lowland area adjacent to Nansen Sound and Eureka Sound is sheltered from the direct effects of cold air masses originating over the polar pack ice by the surrounding mountains and plateau barriers of Axel Heiberg Island. The lowlands experience the greatest mean annual temperature range, 43°C, in the Queen Elizabeth Islands; mean daily January temperatures vary from -35°C to -40°C, while mean daily July temperatures vary from 3°C to 5°C. In contrast, the interior highlands of Axel Heiberg Island, dominated by extensive ice caps, experience a mean annual temperature range of 35°C: mean daily January temperatures vary from -28°C to -32°C, while mean daily July temperatures vary from 0°C to 3°C. Bradley and England (1978) and Maxwell (1981) have reported a marked temperature decrease (i.e. 1.1°C decrease in July mean maximum temperatures)

in this region of the eastern Canadian High Arctic from 1950s through the 1970s. Variations of the depth of melt layers observed in ice cores indicate that the summers over the past century have been the warmest for more than 1,000 years leading to negative mass balances for glaciers and ice sheets throughout the archipelago (Bradley, 1990).

Lowlands are protected from cyclonic activity by the surrounding highlands, which results in the lowest mean annual precipitation in Canada (less than 100 mm), of which 35-40% falls as rain. On the other hand, the adjacent highlands receive greater precipitation (over 200 mm of annual precipitation), of which 20% to 30% falls as rain.

3.5 Permafrost

The soils of the eastern Canadian High Arctic experience an "arctic" soil temperature regime (Maxwell, 1980). The primary criterion for this designation is that mean annual soil temperatures be less than -6.7°C with a mean summer soil temperature of less than 5°C. Taylor (1991) observed a mean ground-surface temperature of -15.3°C at a site immediately north of the study area. The ground temperature reconstruction at this site suggests a short, intense Little Ice Age (ca. 100 to 200 a BP) climate during which ground-surface temperature was about 5 ^{o}C lower than today. The cold ground temperatures have contributed to the formation of permafrost and the aggradation of massive ground ice within fine-grained glaciomarine sediments below Holocene marine limit in the study area. The maximum depth of permafrost exceeds 500 meters (Taylor, 1991). Active layer depths vary from 40-100 cm depending on the nature of the surficial materials, being deeper in dry gravel and shallower in moist silt and peat (Maxwell, 1980; Pollard, 1991).

3.6 Depositional Environments

The shell collections were recovered from sediments representing a variety of glacial and post-glacial sedimentary environments (Figure 3.3). Information on texture, bedding characteristics, physical and biogenic sedimentary structures, and stratigraphic position relative to sea level have been combined to identify seven sedimentary facies: Facies 1-4 have been observed throughout the study area, and Facies 5-7 are restricted to the southern coast of the study area (Bell & Aitken, in prep.).

Figure 3.3 Photograph of an outcrop of fossiliferous marine sediments within the study area illustrating the excellent preservation of *in situ* marine molluscs.

Facies 1 (diamicton) consists of poorly sorted, massive, stony silt often containing shell debris. This facies occurs as a thin veneer (less than 1 m thick) with a patchy distribution throughout the study area, notably above Holocene marine limit (>130-145

m a.s.l.). The stratigraphic position of these sediments and radiocarbon ages on enclosed shells that range from 29-33 ka BP indicate that these sediments are associated with the advance and retreat of glacial ice in the Late Pleistocene.

Facies 2: (gravel) occurs as a thin veneer of subrounded clasts that overlies various materials including weathered bedrock, diamicton (Facies 1), laminated silt and sand (Facies 3 and 4), and thickly-bedded silt and sand (Facies 7). This facies is strongly associated with raised beach ridges below Holocene marine limit.

Facies 3 (rhythmically laminated sand and silt) occurs as thick accumulations of thinly laminated sand and silt that lie stratigraphically below and in proximity to marine deltas and/or terraces at and below Holocene marine limit. This facies is sparsely fossiliferous. These sediments are physically linked to the deltas and terraces and represent high energy nearshore environments.

Facies 4 (silt) consists of massive, dark-coloured silt, occasionally interbedded with thin sand laminae. Thick accumulations of these sediments occur within the lower reaches of river valleys within the study area. Mollusc shells occur commonly but never abundantly within this facies. These sediments occur stratigraphically below Facies 3 and are physically related to the former sediments, representing low energy nearshore environments.

Facies 5, 6 and 7 are observed at elevations below 40 m asl and only in a single extensive exposure along the southeastern coast of the study area. Facies 5 consists of dark-coloured, massive, pebbly silt with algal debris. The sediments are moderately fossiliferous and characterized by the presence of *in situ* mollusc shells, including the rare taxa, *Mya pesudoarenaria*. Kelp holdfasts were observed attached to pebbles in

these sediments. Facies 6 consists of planar or lenticular bedded, pebbly sand and gravel with algal debris. Planar tabular cross-bedding is preserved in some beds. These sediments are sparsely to moderately fossiliferous and exhibit the most diverse molluscan shell assemblages recorded in the study area. Facies 7 consists of thin to thickly bedded fine to medium sand. Individual beds are normally graded and capped by thin silt laminations. The sediments are sparsely fossiliferous but exhibit pervasive bioturbation recorded by numerous dark-coloured, clay-filled burrows. These three facies are arranged stratigraphically from Facies 5 near or at the base of measured sections, through Facies 6, to Facies 7 at the top of measured sections. A veneer of gravel (Facies 2) commonly overlies Facies 7. The preservation of *in situ* mollusc shell assemblages and kelp holdfasts within massive fine-grained sediments suggest deposition in a low energy nearshore environment for Facies 5. The coarser sediments (dominantly sand with some gravel), normally graded bedding, and the diverse molluscan shell assemblages associated with Facies 6 and 7 record rapid deposition in a late post-glacial high energy nearshore environment. The distribution of shell samples among the various facies is illustrated in Table 3.1.

Table 3.1 The distribution of shell samples among the depositional environments represented in the study area.

1. Glacial: diamicton	2. Beaches: wave-washed glacial till; gravel	3. Shallow marine: massive silt or interbedded with thin sand laminations	4. Proglacial: rhythmically bedded / laminated silt and sand
ES-01-S-9402			
ES-09-S-9406	ES-03-S-9404		MF-26A/S-0898
ES-10-S-9407	ES-05-S-9405		MF-26C/S-0898
ES-11-S-9408	ES-08-S-9405	ES-18-S-9421	MF-26D/S-0898
ES-15-S-9418	MF-27-S-0998	MF-12-S-2998	MF-26E/S-0898
ES-17-S-9421	ES-Sh3-0807	MF-13-S-2998	ES-Sh8-0802
MF-16-S-0198	ES-Sh4-0807	MF-14-S-3098	ES-Sh25-1007
MF-20-S-0398		MF-18-S-0298	
MF-21-S-0498		MF-19-S-0298	
		MF-23-S-0598	
		ES-Sh5a-0807	
		ES-Sh5b-0807	
		ES-Sh6-0807	

5. Shallow marine or estuarine: pebbly sand and gravel with algal debris	6. Shallow marine or estuarine: pebbly silt with algal debris	7. Shallow marine or estuarine: interbedded silt and sand
	ES-04A-S-9404	ES-Sh10-0907
ES-04D-S-9404	MF-28-S-0998	ES-Sh17-0907
ES-04E-S-9404	MF-29-S-0998	ES-Sh18-0907
ES-04F-S-9404	ES-Sh2-0707	ES-Sh19-0907
ES-Sh22-0907	ES-Sh9-0907	ES-Sh20-0907
	ES-Sh29-1207	ES-Sh21-0907
	ES-Sh30-1207	ES-Sh23-0907
	ES-Sh31-1207	ES-Sh24-0907
		ES-Sh27-1207
		ES-Sh28-1207
		ES-Sh32-1207
		ES-Sh33-1207

CHAPTER 4 METHODOLOGY

4.1 Taxonomic Analysis

4.1.1 Sample collection and processing

Bulk samples were collected from natural exposures in raised marine sediments and glacial tills using a Mason's trowel. Each sample contains 30+ molluscan shells and the enclosing sediment. Whenever possible samples were recovered from discrete beds; however, in massive sediments shells were recovered from a minimum volume of 1000 cm^3. Shells were extracted from the sediments by washing in distilled water on a 0.5 mm sieve. The smaller shells were excluded because: 1) very small shells are not taxonomically identifiable; and 2) small individuals contribute little to the total biomass of the communities since many of them represent juvenile organisms that died soon after larval settlement and thus had been a part of the community for only a short period of time (Kowalewski *et al.*, 1994). Complete shells were separated from shell fragments. Any fragment of shell which included an identifiable umbo (in the case of bivalves) or the spire (in the case of gastropods) was considered as a complete shell. Shells were identified to the level of species using professional taxonomic literature (Macpherson, 1971; Lubinsky, 1980) and reference specimens from the marine invertebrate collection of the Canadian Museum of Nature.

4.1.2 Statistical Analysis

4.1.2.1 Cluster Analysis

The clustering method is an operation by which the set of objects (i.e. mollusc taxa, sampling stations) is partitioned into two or more subsets (clusters) using pre-established rules of agglomeration or division (Legendre and Legendre, 1998). Cluster

analysis is a method of classification of objects in order to find the hierarchical groups in a multivariate data set. The assumptions of cluster analysis include 1) the data set is sensitive to outliers and 2) there is no significant difference between objects. The variables can be interval (ratio scale), binary (presence-absence), or count data. According to the type of data, the clustering method and the measure of distance between two objects can be selected to calculate the proximity matrix (the distance or similarity matrix) and to agglomerate objects (to combine the clusters according the distances between the objects or clusters being combined).

There are two clustering methods: one that operates on variables (R-mode) and the other on objects (Q-mode). In the ecological or biological sense, variables may be species abundance or presence/absence, whereas the objects are sites, stations, or samples. Q-mode analysis clusters samples by comparison of distances or similarities between samples. The result is expected to reveal that samples from similar environments tend to cluster closer to each other than to samples taken from other environments. R-mode analysis, which clusters the species based on the samples in which they are contained, illustrates relationships between species that commonly occur together.

For this study, the presence-absence (binary) data for 27 taxa represented in the 55 samples were set as variables (refer to Appendix I: Table 1). The criteria for inclusion of taxa in the cluster analysis are: 1) taxon abundance is equal to or greater than 5% of total specimen abundance in any given sample; 2) the taxon must be present in two or more samples. Eleven of the 27 taxa meet these criteria (*Nuculana pernula*, *Portlandia arctica*, *Musculus* sp., *Astarte* sp., *Serripes groenlandicus*, *Macoma* sp., *Mya* sp.,

Hiatella arctica, *Pandora glacialis*, *Thracia myopsis*, *Buccinum* sp). Q-mode and R-mode Hierarchical Cluster Analysis were conducted with the appropriate protocols in SPSS version 12.0, using the within-groups linkage for the clustering method and the Jaccard similarity ratio (an index in which joint absences are excluded from consideration (4.1); equal weight is given to matches and nonmatches) for the distance measure (Sokal and Michener, 1958; Quinn and Keough, 2002). The Jaccard similarity ratio is determined as follows:

$$1\text{-}a / (a + n_i + n_j) \qquad (4.1)$$

Let a be the number of variables with non-zero values in both objects, n_i is the number of variables with non-zero values in object i, and n_j is the number of variables with non-zero values in object j (Quinn and Keough, 2002).

Q-mode clustering identifies similarities among the 55 samples, and R-mode clustering identifies similarities among the 11 taxa. We combined the presence of several taxa in order to include *Mya* sp., *Macoma* sp., *Astarte* sp. and *Musculus* sp. in the cluster analysis. These data are displayed in the cross-plot that appears as Figure 5.1 in Chapter 5.

4.1.2.2 Multidimensional Scaling

Illustrating data more visibly, Multidimensional Scaling (MDS) was used to complement the cluster analysis. MDS is a data reduction technique which is similar to factor analysis (Legendre and Legendre, 1998; Quinn and Keough, 2002). In factor analysis, similarities between objects are illustrated in a correlation matrix between objects (a matrix of correlation coefficients between each two different variables), whereas in MDS, any kind of similarity, dissimilarity or multivariate matrix can be analyzed including a correlation matrix (see SPSS Inc, 2003; Quinn and Keough, 2002). By assigning objects to specific locations in a conceptual space in which the distances

between points match the given dissimilarities as closely as possible, MDS attempts to arrange objects in a space with a particular number of dimensions (two or three generally) so as to make the data easily observed and understood. The procedure is relatively free of distributional assumptions: the correlation matrix can be dissimilarity data or multivariate data, and variables can be quantitative, binary, or count data (Bray and Curtis, 1957; McCloskey, 1970; Boesch, 1973; Heip, 1974; Stewart *et al.*, 1985; Schmid and Peipenberg, 1993).

The same dataset (11 taxa; 55 samples) was also analyzed with multidimensional scaling (MDS), using the binary Lance and Williams nonmetric measure (also known as the Bray-Curtis nonmetric coefficient) in SPSS version 12.0. The Lance and Williams nonmetric measure is determined as follows:

$$1-2a / (2a + n_i + n_j) \quad (4.2)$$

Let a be the number of variables with non-zero values in both objects, n_i is the number of variables with non-zero values in object i, and n_j is the number of variables with non-zero values in object j (Quinn and Keough, 2002).

The analysis was performed on both taxa and sample data sets using the same measure method.

4.2 Taphonomic Analysis

4.2.1 Classification of taphonomic features

Observations of taphonomic features allow for the construction of taphograms that illustrate the degree of preservation of each sample according to the taphonomic literature (Kidwell, 1986; Speyer and Brett, 1988b; Brett and Speyer, 1990; Pickerill and Brenchley, 1991). The preservation features examined in this study include: 1) the degree of shell fragmentation; 2) the degree of shell corrasion; 3) the degree of

bioerosion; 4) the degree of encrustation; and 5) skeletal sorting (Table 4.1). Each shell was compared to a set of reference specimens of that particular species. Each reference specimen displayed one of three taphonomic grades: “good”, “fair”, or “poor”. The criteria of each grade for each preservation feature are described as below:

1) Fragmentation

This feature describes the extent to which each shell has been broken. A shell that exhibits little or no fragmentation was rated as “good”; a shell was rated as “fair” with less than 50% of the shell fragmented; a shell with more than 50% fragmented was rated as “poor”.

2) Corrasion

This feature represents a combination of corrosion (chemical weathering or dissolution of the shell) and abrasion (mechanical weathering). It shows the extent to which the surface of the shell has been degraded. A “good” shell displays minimal to no effects of corrosion: the external ornamentation of the shell is unaffected and the pallial line and muscle scars on the internal surface are clearly demarcated. A shell was rated as “fair” if the colour or luster of the shell has been lost, some chalkiness is evident, and the pallial line and muscle scars are faint: the shell has undergone some corrasion. If the shell has completely lost its colour and/or luster, it is completely chalky, and the pallial line and muscle scars are not visible, the shell was rated as “poor”.

3) Bioerosion

This character describes the extent to which shells have been bored by sponges, algae, or other macroscopic endobionts. A “good” shell displayed no evidence of bioerosion; a “fair” shell is characterized by less than 25% of the surface area affected

by bioerosion; a “poor” shell has more than 25% of the surface area affected by bioerosion.

4) Encrustation

This character represents the extent to which the shell surface was covered by bryozoans, barnacles, calcareous algae, or other epibionts. A shell with no coverage by encrusting organisms was rated as “good”; a shell with less than 25% coverage was rated as “fair”; a shell with more than 25% coverage was rated as “poor”.

5) Skeletal sorting

Bivalve shells had been identified as left or right valves according to literature (Abbott, 1974; Lubinsky, 1980). The sum was recorded for both left and right valves separately for each individual sample. In terms of size sorting, the length of each shell (the distance from anterior to posterior (Abbott, 1974)) was measured by calipers of precision 0.1 mm and recorded for each species, including bivalves and gastropods.

4.2.2 Cluster Analysis

To identify the pattern of shell preservation among the various samples, hierarchical cluster analysis was conducted by using between-groups linkage for the clustering method and squared Euclidean distance (the sum of the squared differences between the values for the objectives) for the distance measure (SPSS Inc, 2003). Fifty-five samples are set as variables and the four taphonomic features (fragmentation, corrasion, bioerosion, and encrustation) are set as objects. R-mode analysis (on taphonomic features) and Q-mode analysis (on samples) were conducted, based on the mean grade of taphonomic features.

Table 4.1 Taphonomic variables used to describe the taphonomic properties of shells in this study.

Taphonomic variable	Description	Units of measurement	Taphonomic grades (ranks) 0 (good)	1 (fair)	2 (poor)
Fragmentation	Mechanical taphonomic feature describing the extent to which each valve was broken	Not applicable	Shell without any fragmentation	Less than 50% of the shell fragmented	More than 50% fragmented
Corrasion	Mechanical taphonomic feature (combination of corrosion and abrasion) describing the extent to which the general surface was degraded	Not applicable	Shell with minimal to no effects of corrasion (unaffected external ornamentation, clear pallial line and muscle scars)	Colour or luster of shell lost; some chalkiness; faint pallial and muscle scars	Shell has completely lost colour luster; extensive chalkiness; pallial line and muscle scars not visible
Bioerosion	Biological taphonomic feature describing the extent to which shells is bored by macroscopic endobionts	Not applicable	Shell displayed no evidence of bioerosion	Shell affected less than 25%	Shell affected more than 25%
Encrustation	Biological taphonomic feature describing the extent to which the shell surface is covered by epibionts	Not applicable	Shell with no coverage by encrusters	Shell with less than 25% coverage of encrustation	Shell with more than 25% coverage of encrustation
Supplementary Variables					
Valve size and sorting	Identification of right/left valves; shell size	Left/right valve ratios; shell length in millimeters	Not applicable		

4.2.3 Taphograms

Fursich and Flessa (1991) use the term "taphogram" to refer to a frequency distribution of taphonomic features. Each taphonomic feature was rated on a three-level

grade scheme ("0", "1", "2"), the mean grade (0~2) for each species in terms of each taphonomic feature can be determined.

Kowalewski *et al*. (1994) and Kowalewski *et al*. (1995) developed the ternary taphogram, which allows a sample to be represented as a single point on a triangular graph. The three level grade adopted in this study facilitates the use of ternary taphograms to examine variations in shell preservation among samples. Figure 4.1 illustrates the scheme.

Ternary taphograms have been plotted for four abundant species (*Hiatella arctica*, *Mya truncata*, *Astarte borealis*, *Serripes groenlandicus*) in all samples. The advantages of this approach are manifest: 1) a single point can represent a sample's frequency distribution of taphonomic grade, and 2) a single point on the ternary taphogram contains more information than a sample's average taphonomic score (i.e., mean taphonomic grade), because this score cannot demonstrate the nature of the variation in taphonomic condition. Three classes are required to be defined along a continuum of preservational quality, however, and the meaning of such taphonomic grades as "good", "fair", and "poor" are likely to differ from investigator to investigator (Kowalewski *et al*., 1995). Another potential disadvantage is the limitation to only three taphonomic grades since the range of taphonomic variation may require more than the three categories in some cases.

4.2.4 Valve ratios

The number of left and right valves was pooled for each of four common bivalve species (*Hiatella arctica*, *Mya truncata*, *Astarte borealis*, *Serripes groenlandicus*) to test the difference between the ratios of left and right valves. The ratio of left and right

valves was compared with the expected value of 1:1 by chi-squared test for each taxon in each of the 55 samples (Chapman and Schaufele, 1970; Quinn and Keough, 2002). Separate tests were also conducted on groups of samples from each of the seven depositional environments (see Table 4.2), in order to examine patterns within the study area.

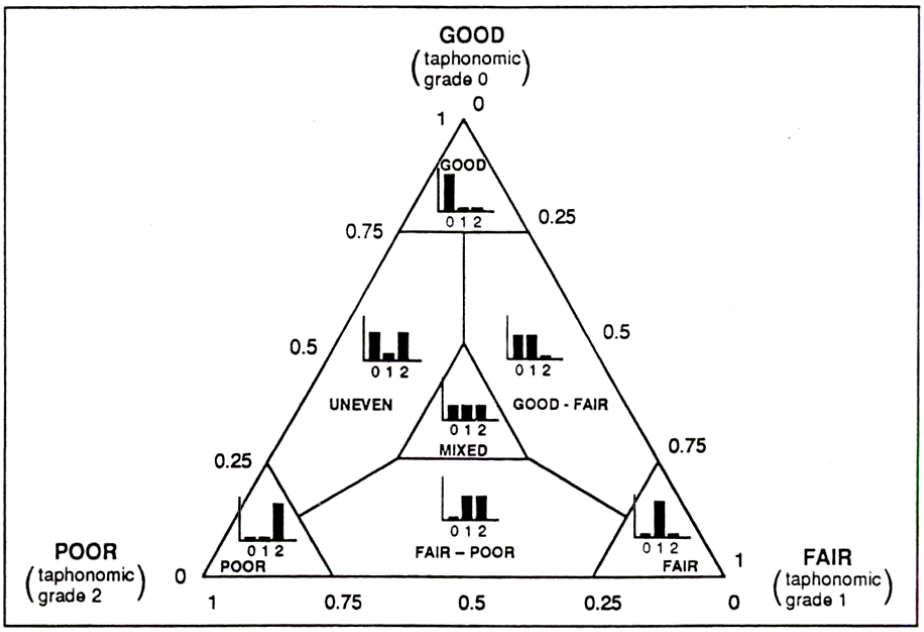


Figure 4.1 The ternary taphogram. Each corner of the taphogram represents a particular taphonomic grade. The location of a particular sample on the ternary taphogram is determined by the proportion of specimens in "good" (0), "fair" (1), or "poor" (2) condition. The histogram within each field ("good", "uneven", "mixed", etc.) on the diagram illustrates the variation of taphonomic grades in a sample within that field. Adopted from Kowalewski *et al*. (1994).

4.2.5 Valve size

Data for the length of bivalve shells and the height of gastropod shells were pooled at the species level in groups of samples from the same depositional environment. Descriptive statistics (mean, median, mode, standard deviation, minimum and

maximum values, kurtosis, and skeweness) were determined for the three most common bivalve species (*Hiatella arctica*, *Mya truncata*, *Astarte borealis*) in SPSS version 12.0.

4.3 Guild Analysis

Guilds in paleo-communities can be determined only for single collections or a few closely spaced (either stratigraphically or geographically) collections (Bambach, 1983). Our collecting from discrete sedimentary beds produces samples that were preserved together and represent at least the shortest available time span. The species in our collection are assigned to guilds by 1) recognizing the Class (Bivalvia or Gastropoda) to which each species belongs, 2) identifying the feeding mode, food source, and life habit of life position of each species. The relative abundance represents the number of individuals within a specific guild divided by the total number of individuals from all the species.

CHAPTER 5 RESULTS

5.1 Results of Taxonomic Analysis

5.1.1 Taxonomy and Ecology

A total of 5065 specimens (5018 valves of bivalve and 47 gastropod shells) have been identified and classified into 27 taxa. The bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* are the most common species represented in 55 samples from three localities (Gibbs Fiord, Mokka Fiord, and Eureka Sound, Table 5.1). The dominance of bivalves (99.07%; n = 5018) with respect to gastropods (0.93%; n = 47) and the dominance of suspension feeders (96.78%; n = 4902) in terms of feeding mode are recorded in Table 5.2. The autoecology and biogeographic patterns of the 27 mollusc species are summarized in Table 5.3. A systematic list of 27 identified taxa recorded in this study is presented in Appendix II A. Low diversity faunas characterized by the presence of *Hiatella arctica*, *Mya truncata*, *Astarte* spp., and *Serripes groenlandicus*, were recorded from the Gibbs Fiord and Mokka Fiord regions. More diverse faunas were recorded from glaciomarine sediments in the southern portion of the study area bordering Eureka Sound.

Table 5.1 Taxonomic composition of raised marine sediments and glacial tills from Eureka Sound, Gibbs Fjord, and Mokka Fjord

| Location | Eureka Sound | | |

Table 5.2 Species composition and structure of the fossil molluscan assemblages.

Taxonomic composition		Species Number	Relative abundance
Faunal composition			
Bivalve		20	99.07%
Gastropod		7	0.93%
Ecological characterization			
Life habit	Infauna	16	68.59%
	Epifauna	11	31.41%
Feeding mode	Suspension	14	96.78%
	Deposit	7	2.41%
	Carnivore	5	0.75%
	Browser	1	0.06%

5.1.2 Cluster Analysis

The results of the cluster analysis for 11 taxa and 55 samples are summarized in Figure 5.1. The Q-mode analysis (shell assemblages) identified five distinct groups: combinations of numbers and letters were assigned to each distinct cluster or sub-cluster to distinguish one from another. Group 1 consists almost exclusively of the infaunal deposit-feeder *Portlandia arctica.* Group 2 consists almost exclusively of infaunal suspension-feeders *Astarte borealis* and *A. montagui*. Samples in Group 3 are characterized by the presence of *Mya truncata*. Group 4 consists mostly of the suspension-feeders *Hiatella arctica* (68.3%, n = 869) and *Mya truncata* (27.1%, n = 345). Groups 5 can be sub-divided into two clusters: Groups 5A and 5B. Group 5A contains the most diverse shell assemblages. The criteria that these two sub groups are clustered are the presence of *Serripes groenlandicus* in Group 5A and its absence in Group 5B.

Table 5.3 Autoecology and biogeographic patterns of the mollusc species recorded in this study.

Taxa	Guild	Substrate type	Depth range (m)	Normal minimum salinity (‰)	Temperature * (°C)	Geographic distribution	Geological range**
Nucula belloti	ID	C	5 to 100	Euryha	-1 to 8	H.Arc	(Cret) Pli-R
Nuculana pernula	ID	G, S, C	9 to 40	25	-2 to 14(8)	Arc-Bor	(Tria) Mio-R
Portlandia arctica	ID	C	4 to 81	26	-2 to 4	H.Arc	(Eoc) Pleist-R
Musculus niger	RES	Var	7 to 50	19	-1 to 14	Arc-Bor	(Jur) Pli-R
M. discor	RES	Var	25 to 95	19	-1 to ?	Arc-Bor	Pli-R
M. corrugatus	RES	Var	n/d	n/d	-1 to 10	Arc-Bor	n/d
Thyasira sp.	ID	Var	2 to 385	23-33	n/d	Arc-Bor	Pli-R
Astarte borealis	IS	S+C, G	Int to 50	15	-2 to 15.5	Arc-Bor	(Jur) Pli-R
Astarte montagui	IS	C+S	Int to 70	19	-2 to 14	Arc-Bor	n/d
Clinocardium ciliatum	IS	C, G+S	9 to 20	Euryha	-2 to 9	Arc-Bor	(Eoc) Mio-R
Serripes groenlandicus	IS	S+C	Int to 50	Euryha	-2 to 9	Arc-Bor	(Mio) Mio-R
Macoma calcarea	ID/S	S, C, S+C	Int to 124	13	-2 to 16(11)	Arc-Bor	(Eoc) Mio-R
M. moesta	ID/S	S+C	7 to 47	32	-1.5 to 7.5	Arc-Bor	(Eoc) Pleist-R
M. loveni	ID/S	Var	5 to 200	32	-3 to 9	H. Arc	n/d
Mya pseudoarenaria	DIS	Var	6 to 185	28	-2 to 11	Arc	?-Pleist
Mya truncata	DIS	Var	Int to 103	17	-2 to 17	Arc-Bor	(Eoc) Mio-R
Hiatella arctica	SIS	Var	Int to 50	20	Euryth	Arc-Bor	(Jur) Olig-R
Lyonsia arenosa	SIS	S+C, S	11 to 16	32	-2 to 8.5	Arc-Bor	(Eoc) Pleist-R
Pandora glacialis	IS	S, S+C	2 to 205	32	-1 to 8	H.Arc	n/d
Thracia myopsis	IS	S	2 to 350	n/d	-2 to 11	Arc	n/d
Margarites olivaceus	G	M	5 to 384	n/d	n/d	Arc-Bor	(Eoc)-R
Trichotropis borealis	ES	G, S, C	4 to 32	Stenoh ?	14?	Arc-Bor	(Cret) Plio-R
Buccinum finmarkianum	EP	Var	5 to 40	n/d	n/d	Arc-Bor	(Eco) Pli-R
Buccinum cf *totteni*	EP	Var	9 to 80	n/d	n/d	Arc-Bor	n/d
Colus cf *togatus*	EP	C, S	shallow	n/d	n/c	Arc-Bor	(Eoc)-R
Oenopota cf *cinerea*	IP	C	4.5 to 52	n/d	-2 to 15	Arc-Bor	n/d
Cylichna sp.	EP	G, S, C	n/d	n/d	0 to 10	Arc-Bor	(Cret) Pleist-R

Explanations of the symbols:
ID: siphonate palp-probiscide deposit-feeder; RES: reclining epibyssate suspension-feeder; IS: siphonate shallow infaunal suspension-feeder; ID/S: siphonate surface deposit-/suspension-feeder; DIS: sluggish siphonate deep infaunal suspension-feeder; SIS: endobyssate (semi-infaunal) suspension-feeder; G: spired grazers; ES: epifaunal suspension-feeder; EP: epifaunal predators; IP: infaunal predators.
C: clay; G: gravel; S: sand; M: macroalgae; Var: variable (clay, sand, gravel, or rock).
Int: intermareal; shallow: < 200 m.
Euryha: euryhaline; Stenoh: stenohaline; Euryth: eurythermic.
Arc: Arctic; Arc-Bor: Arctic-Boreal; H.Arc: High Arctic.
Tria: Triassic; Jur: Jurassic; Cret: Cretaceous; Pal: Paleocene; Eoc: Eocene; Olig: Oligocene; Mio: Miocene; Pli: Pliocene; Pleist: Pleistocene; R: Recent.
n/d: no data; ?: with doubt.
(*) minimum summer temperature
(**) genus range between brackets
References:
Ockelmann (1958); Macpherson (1971); Abbott (1974); Marincovich *et al*. (1985); Vermeij (1991); Peacock (1993); Suzuki and Akamatsu (1994); Crame (1996); Gordillo and Aitken (2000).

Astarte spp. (*Astarte borealis* and *A. montagui*) exhibit more abundant (40.2%, n = 857) than the other three dominant species in Group 5A; *Hiatella arctica* (19.9%, n = 424), *Serripes groenlandicus* (19.2%, n=409) share similar abundance; and *Mya truncata* (13.9%, n = 296) exhibit less abundant in the cluster. In Group 5B, *Mya truncata* are most dominant (40.3%, n = 435) followed by *Astarte* spp. (26.8%, n = 289) and *Hiatella arctica* (23.0%, n = 248) respectively.

The R-mode (taxa) analysis produced two clusters. The first group is characterized by bivalve taxa including all of the four common taxa, *Hiatella*, *Mya*, *Astarte* and *Serripes*, and two other less common taxa, *Macoma* and *Portlandia*. The second group consists exclusively of rare bivalve taxa, *Pandora*, *Musculus*, *Thracia* and *Nuculana*, and the gastropod taxon, *Buccinum*.

5.1.3 Multidimensional Scaling

Figure 5.2 and Figure 5.3 shows the results of multidimensional scaling. Three groups can be recognized according to the Euclidean distance model for taxa in Figure 5.2: infaunal suspension-feeding taxa, infaunal deposit-feeding taxa, and a group of rare taxa. The rare taxa where recorded in several samples from estuarine sediments (Facies 5, 6 and 7) recovered at several closely spaced sampling sites near sea-level at the southern boundary of the study area: these taxa are not observed elsewhere in the study area.

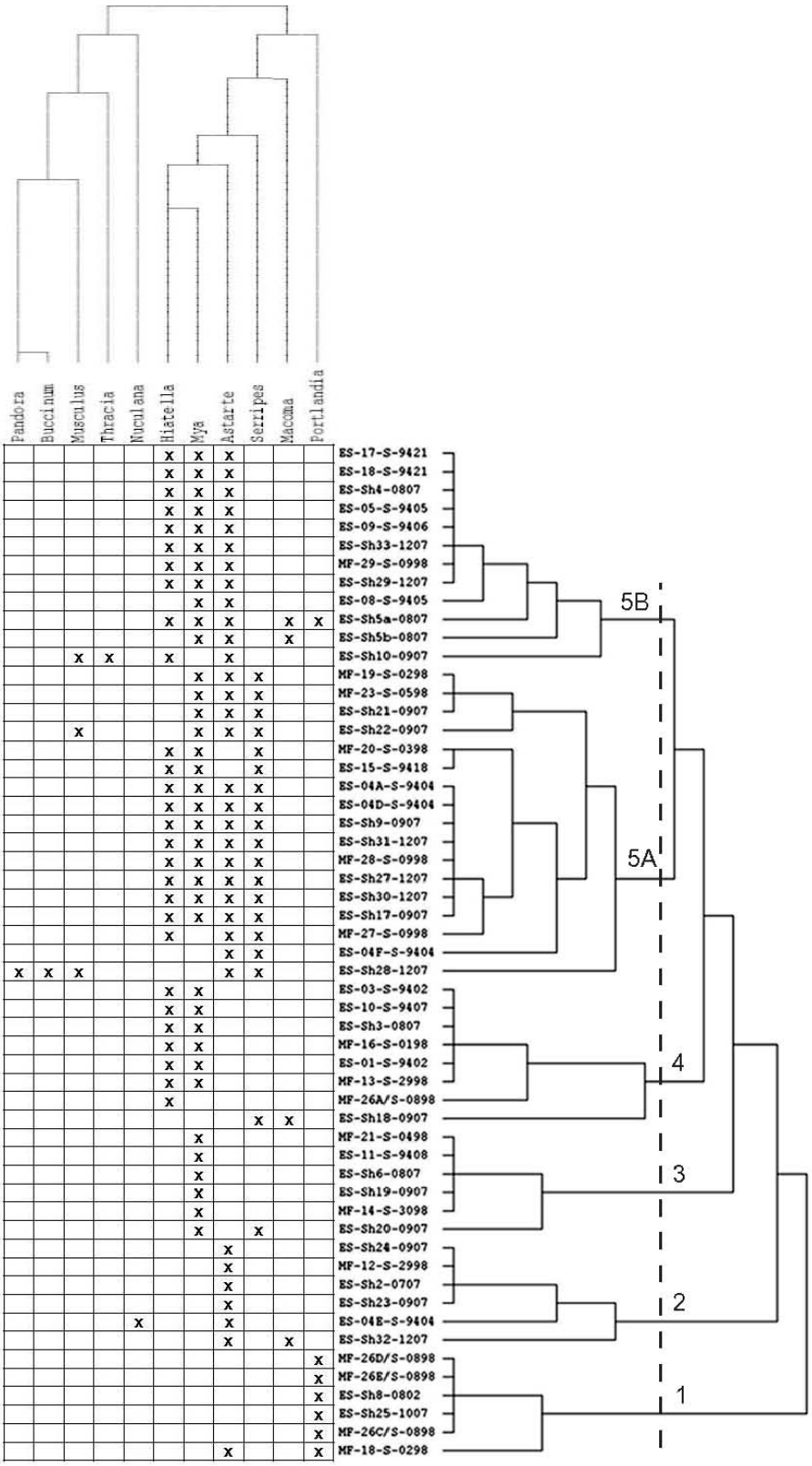


Figure 5.1 Cross-plot of Q-mode and R-mode cluster analysis (presence-absence data pooled at sample and taxon level, respectively).

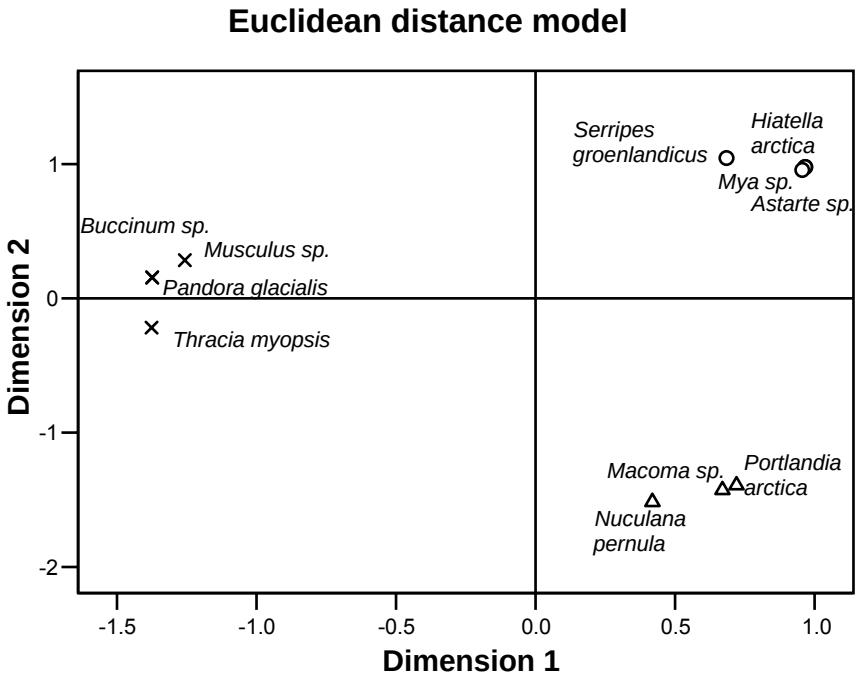


Figure 5.2 The Euclidean distance model from MDS analysis on eleven taxa, where three groups are identified in the rounded rectangular callout and marked: cross (×) = rare taxa, circle (O) = infaunal suspension-feeding taxa, triangular (↖) = infaunal deposit-feeding taxa.

The Euclidean distance model in Figure 5.3 illustrates the clear separation between Group 1 (*Portlandia* dominated) and Group 2 (*Astarte* dominated) on one hand, and Group 3 (*Mya* dominated) and Group 4 (*Hiatella-Mya*) on the other hand. Group 5 shares affiliation with Group 2 and Group 4. Figure 5.4 is linked with seven facies identified from the associated sediments (Chapter 3.6 and Table 3.1). Facies 1 (glacial) and Facies 4 (proglacial) are separated with Facies 5 (shallow marine or estuarine: pebbly sand) and Facies 6 (shallow marine or estuarine: pebbly silt) by the horizontal zero line in the figure. Facies 2 (beaches), Facies 3 (shallow marine: massive silt), and

Facies 7 (shallow marine or estuarine: interbedded silt and sand) are associated with the other Facies everywhere in the model.

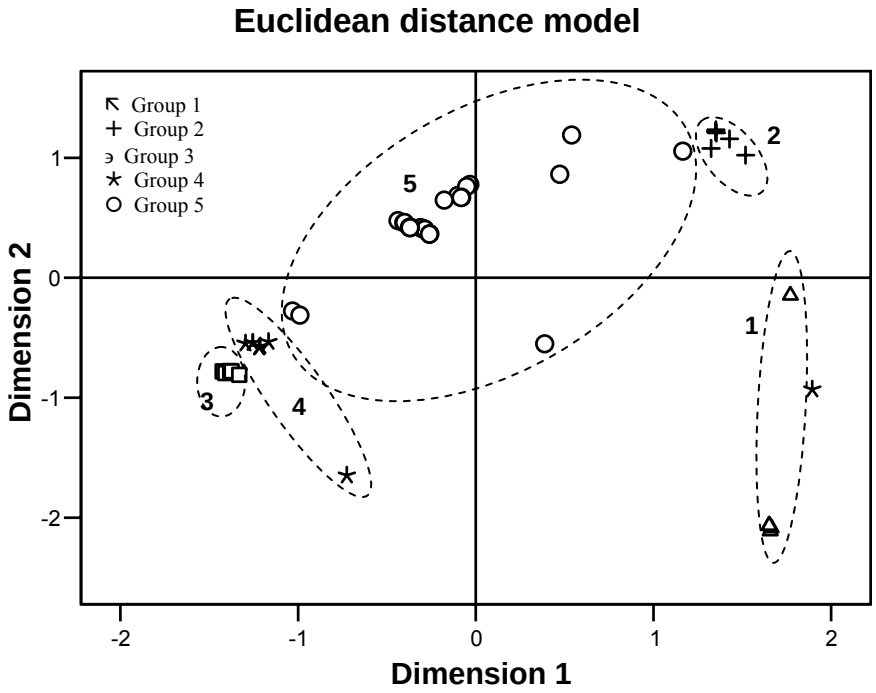


Figure 5.3 The Euclidean distance model from MDS analysis on samples, where the macrofossil associations identified in cluster analysis (Figure 5.1) are marked: triangular (⇖) = Group 1, cross (+) = Group 2, square (▫) = Group 3, star (✶) = Group 4, circle (○) = Group 5.

5.2 Results of Taphonomic Analysis

5.2.1 Taphograms

The taphonomic data are summarized at the sample level for 11 taxa in Appendix I: Table 2A-D. Taphograms have been plotted for 21 distinctive samples illustrated in Figure 5.5**.** These twenty samples were selected because they include the full range of species composition represented in the 55 samples and each of them characterizes a particular cluster produced from the classification in statistical analysis. In some of these examples the various taxa within a sample exhibit roughly identical preservation

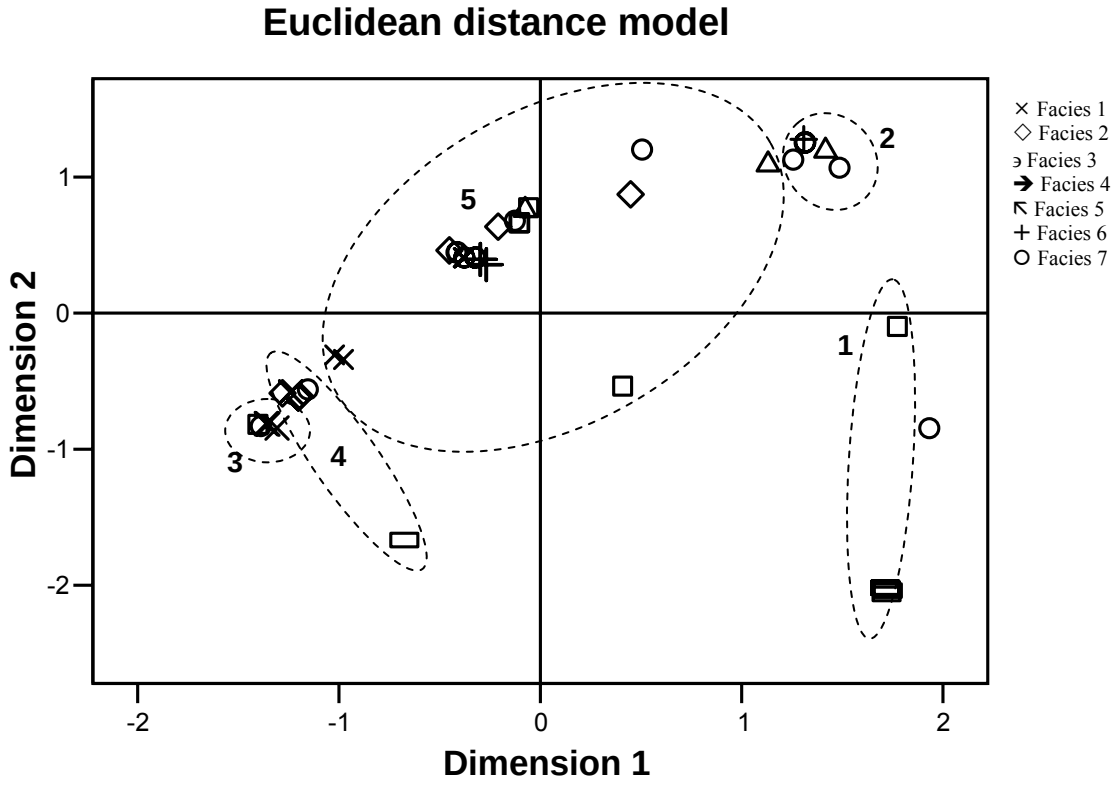


Figure 5.4 The Euclidean distance model from MDS analysis on samples, where the seven facies (Table 3.1) are marked: cross (×) = Facies 1, diamond (◇) = Facies 2, square (ə) = Facies 3, rectangular (➔) = Facies 4, triangular (↖) = Facies 5, cross (+) = Facies 6, circle (○) = Facies 7; and five macrofossil associations identified in cluster analysis (Figure 5.1) are identified by dashed ellipses.

patterns (i.e. MF-18-S-0298, MF-29-S-0998, ES-03-S-9404, ES-04A-S-9404, ES-04F-S-9404), while in other examples different taxa display more complex patterns of shell preservation within a sample (i.e. ES-Sh22-0907, ES-Sh20-0907). For ES-Sh22-0907 which is from Facies 5 (shallow marine or estuarine: pebbly sand), *Serripes groenlandicus* exhibits high fragmentation and corrasion, while the other taxa (*Mya* sp., *Astarte* sp., and *Musculus* sp.) exhibit moderate to low fragmentation and corrasion, at the same time. For ES-Sh20-0907 from Facies 7 (shallow marine or estuarine: interbedded silt and sand), *Serripes groenlandicus* exhibits no fragmentation, whereas

Mya sp. exhibits very high fragmentation. Corrasion in all samples was graded generally as "fair" or "poor"; fragmentation is generally "fair"; bioerosion and encrustation both are graded "good" to "fair" in all twenty one samples.

5.2.2 Cluster analysis

The dendrogram of Q-mode clustering and the resulting distinctive taphonomic pattern are illustrated in Figure 5.6. According to the dendrogram, the samples can be divided into two groups. The first group (Group 1) consists of samples that exhibit a high degree of fragmentation (mean grade = 2.0). Three sub-groups can be further recognized in the first group: one characterized by high scores in corrasion and zero scores for bioerosion and encrustation (MF-14-S-3098); one characterized by intermediate scores for corrasion and zero scores for bioerosion and encrustation (MF-26C-S-0898); and one characterized by high scores for corrasion and low scores for bioerosion and encrustation (ES-09-S-9409). Group 1, therefore, represents samples with poor preservation in terms of fragmentation but with little or no indication of bioerosion and encrustation.

The second group (Group 2) consists of samples with a fair or low degree of fragmentation (mean grade close to or less than 1.0). Group 2 can be further divided into three sub-groups. Group 2A consists of four samples with intermediate scores for all of the four taphonomic features (ES-Sh33-1207). These samples exhibit fair preservation. Group 2B contains more than a half of all the samples (31/55).

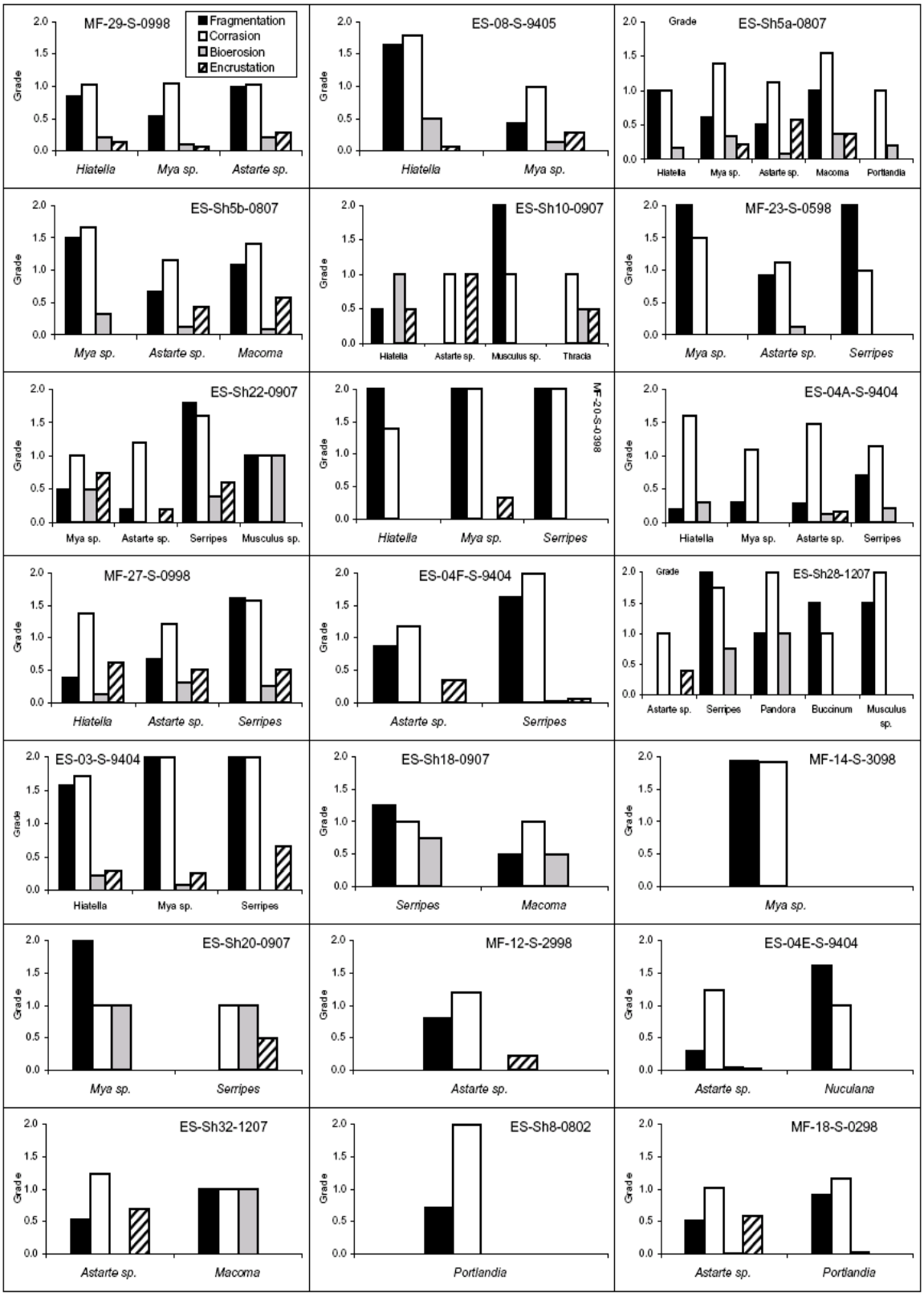


Figure 5.5 Taphograms for 21 distinct samples

Samples in this group exhibit intermediate scores for corrasion and low scores for fragmentation, bioerosion, and encrustation (ES-04A-9404, ES-Sh10-0907). These samples exhibit fair shell preservation. Sample ES-Sh10-0907 and ES-Sh23-0907 are two distinct samples recovered from Facies 7 sediments that exhibit low scores for fragmentation, intermediate scores for corrasion, and low scores for bioerosion and encrustation. These samples exhibit good shell preservation. Group 2C consists of a single sample (ES-Sh8- 0802) and exhibits a high score for corrasion, a low score for fragmentation, and zero scores for bioerosion and encrustation, thus distinguishing it from Group 2B. This sample exhibits fair shell preservation.

5.2.3 Ternary diagrams

Ternary diagrams illustrate clear differences amongst taphonomic variables and seven facies for four common bivalve taxa in Figure 5.7 A-D.

Fragmentation shows great variations among seven facies for *Hiatella arctica* and *Mya truncata*. Facies 1 and Facies 2 group in the left bottom and center bottom parts of the diagrams, while Facies 5 and Facies 6 group in the right top and center right parts of the diagrams. This means that extensively fragmented shells characterize Facies 1 and Facies 2 on one hand, and on the other hand well or moderately preserved shells characterize Facies 5 and Facies 6. Facies 3 and Facies 7 group in the center right and center bottom parts of the diagrams, characterized by a mix of variably fragmented shells with a few extensively fragmented or well preserved shells. For *Astarte borealis*, however, fragmentation shows less variation among Facies 3, Facies 5, Facies 6, and Facies 7, which group in the right-hand side of the diagram with well preserved shells. Facies 1 and Facies 2 group in the bottom part of the diagram, which means extensively

fragmented shells dominate these two facies. For *Serripes groenlandicus*, seven facies group in the center left bottom and center parts of the diagrams, which means most *Serripes* shells are extensively fragmented with only a few fairly preserved shells.

Corrasion shows little variation among the seven facies for all taxa. Except for one sample of *Hiatella* (ES-Sh10-0907) from Facies 7, all the other samples of the four taxa group in the bottom parts of the diagrams, this means that most shells of these four taxa either substantially or completely lose their luster with only a few slightly corroded or abraded shells. Facies 1 and Facies 2 always group in the most left-bottom parts of the diagrams. This means Facies 1 and Facies 2 consist of more extensively corroded or abraded shells than the other Facies do. Compared with the other taxa, *Astarte* exhibits a greater retention of shell luster relative to *Mya* and *Serripes*.

Bioerosion and *encrustation* show a little variation among samples and facies for the four taxa, and most samples group along the "fair" axis of the diagrams. This means the majority of all shells in all facies exhibit little or no evidence of bioerosion or encrustation. A small number of samples from Facies 3 and Facies 7 group on the right bottom parts in the diagrams for both features, exhibiting slightly bioeroded / encrusted.

Portlandia arctica is the only species that is recovered from Facies 4 (proglacial). The shells are considerably fragmented and corroded/abraded, with no evidence of bioerosion and encrustation (Figure 5.8).

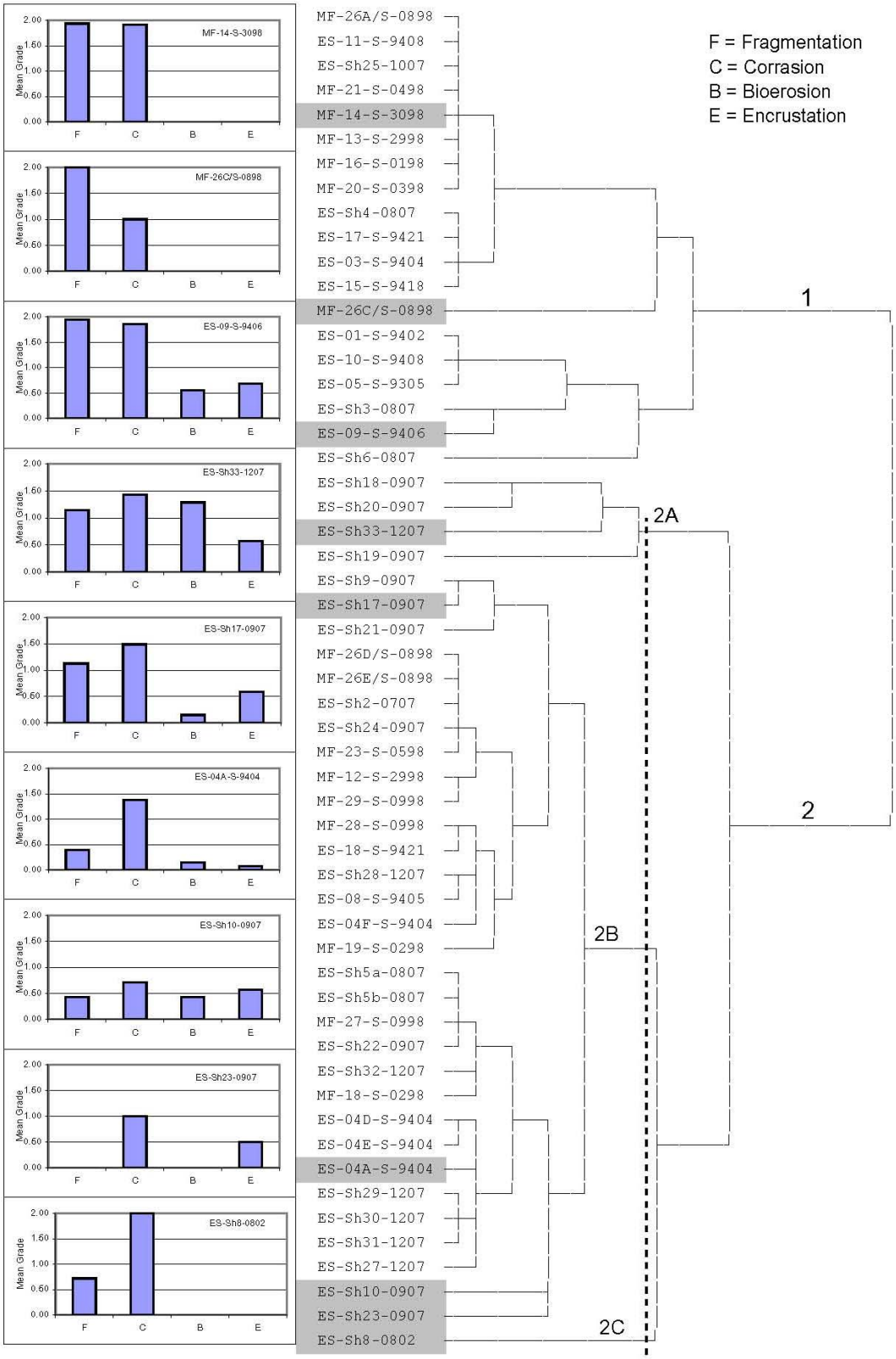


Figure 5.6 Q-mode cluster analysis for the taphonomic grade of all shells for all taxa. The bar graphs illustrate the mean grades for each of taphonomic feature.

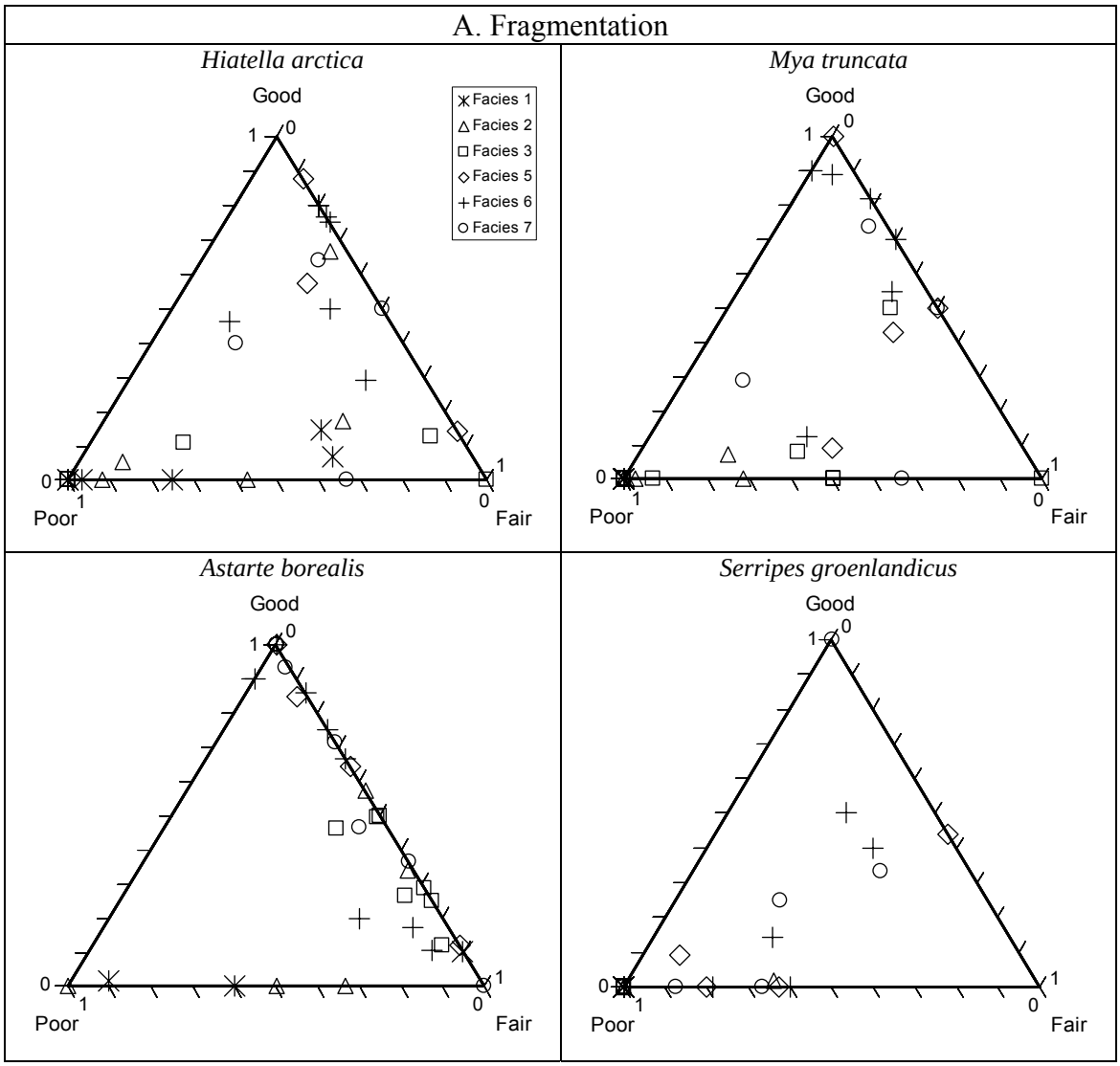


Figure 5.7 A Ternary diagrams of fragmentation for *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus*.

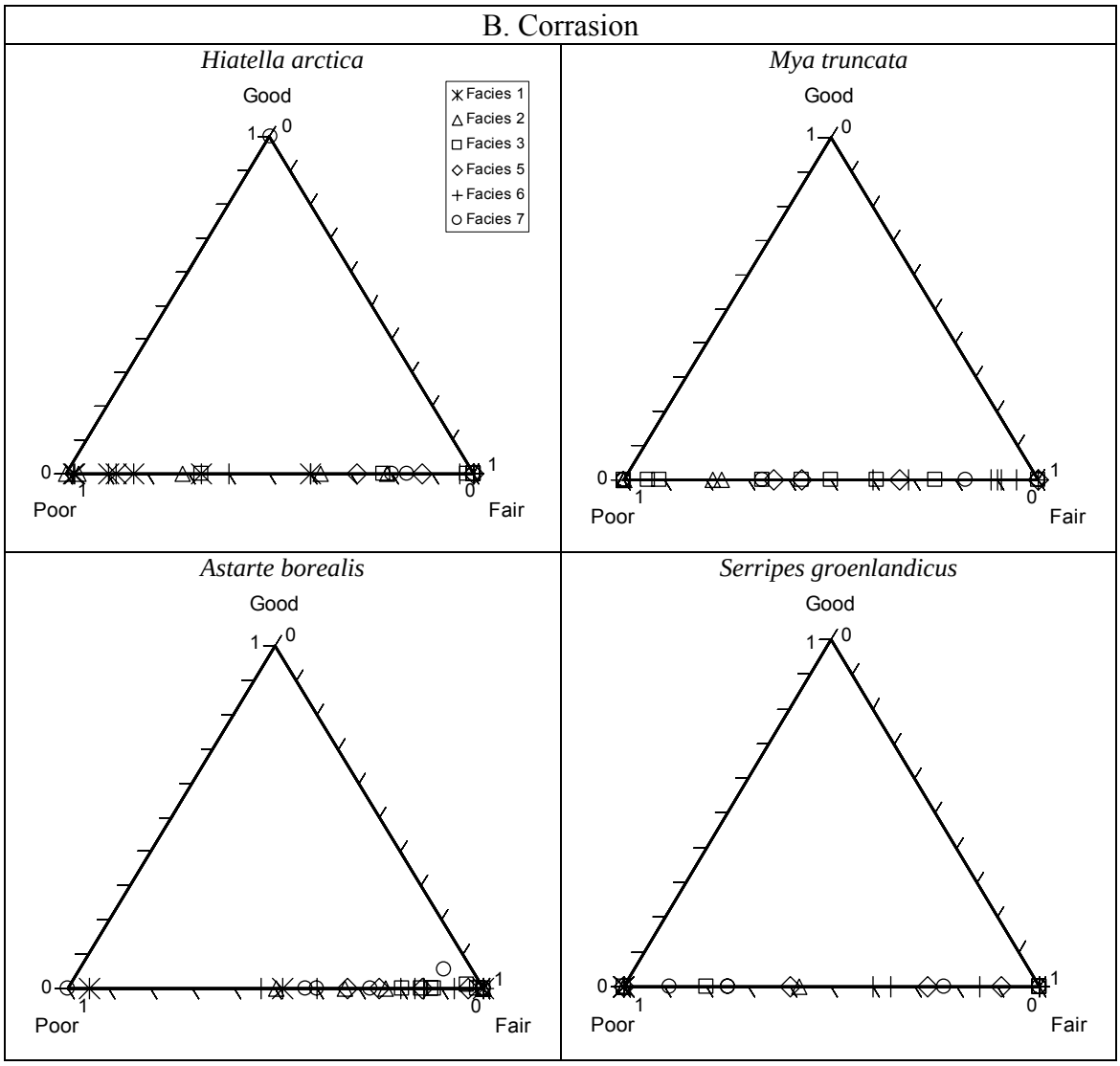


Figure 5.7 B Ternary diagrams of corrasion for *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus*.

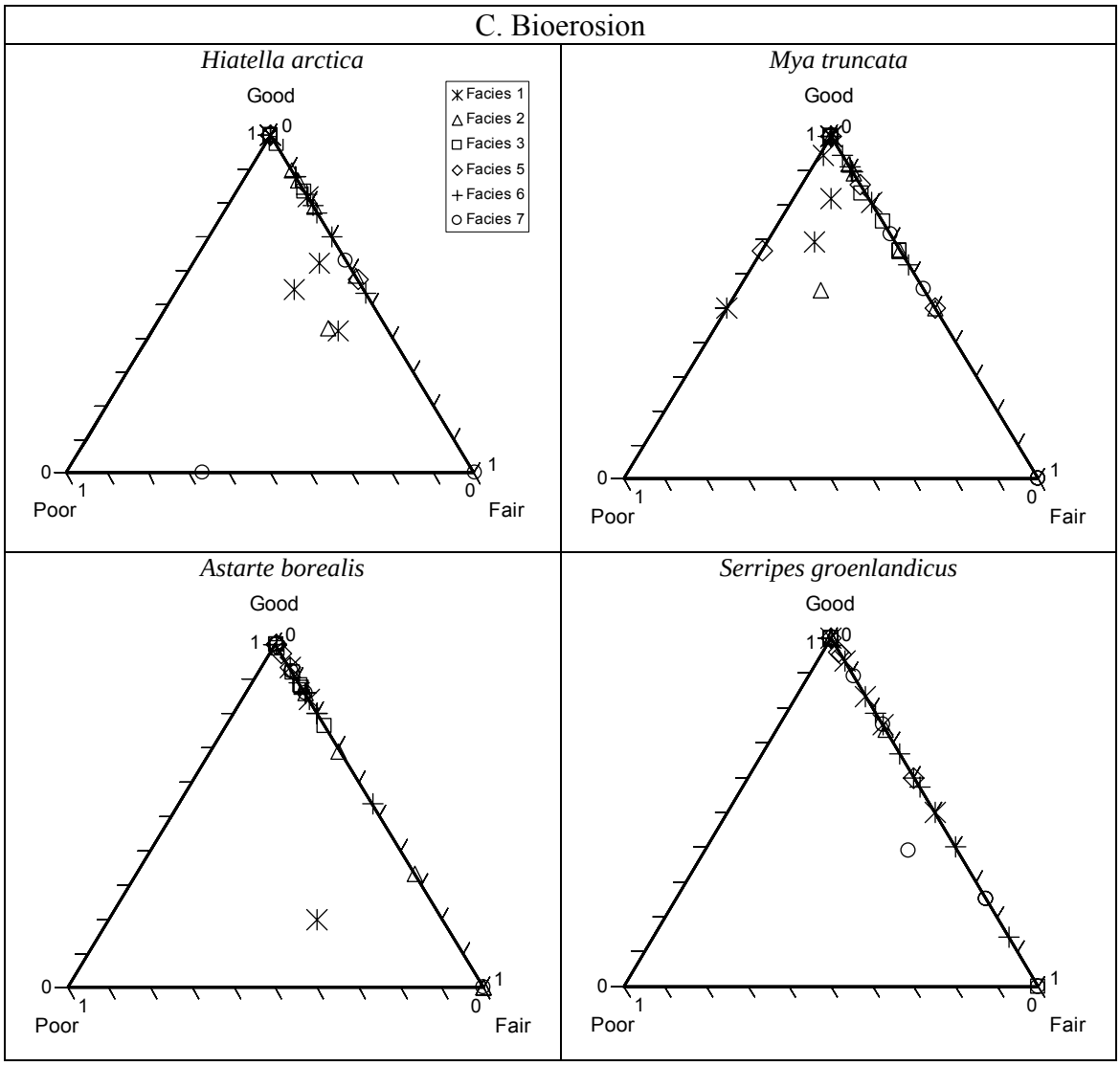


Figure 5.7 C Ternary diagrams of bioerosion for *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus*.

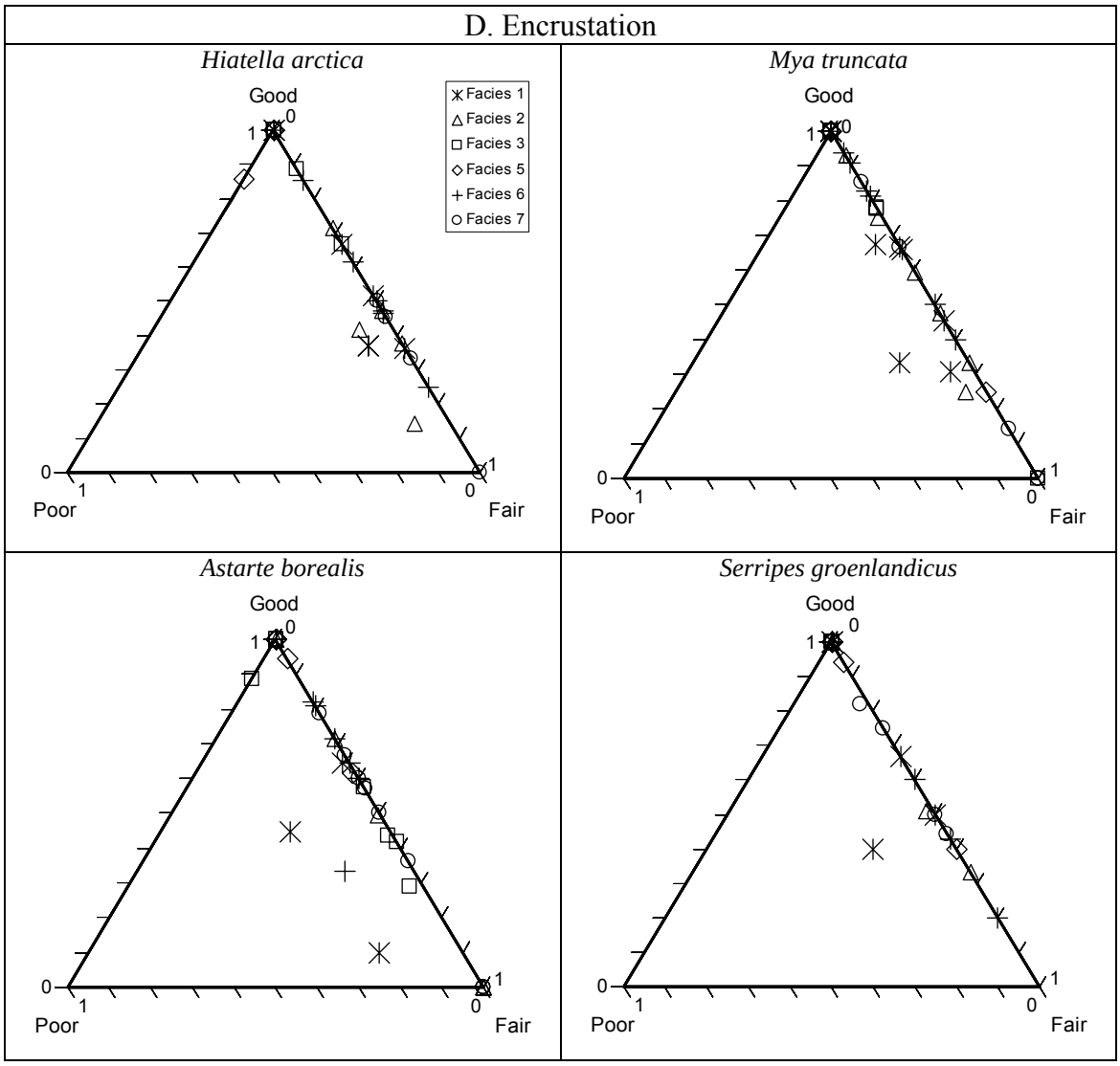


Figure 5.7 D Ternary diagrams of encrustation for *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus*.

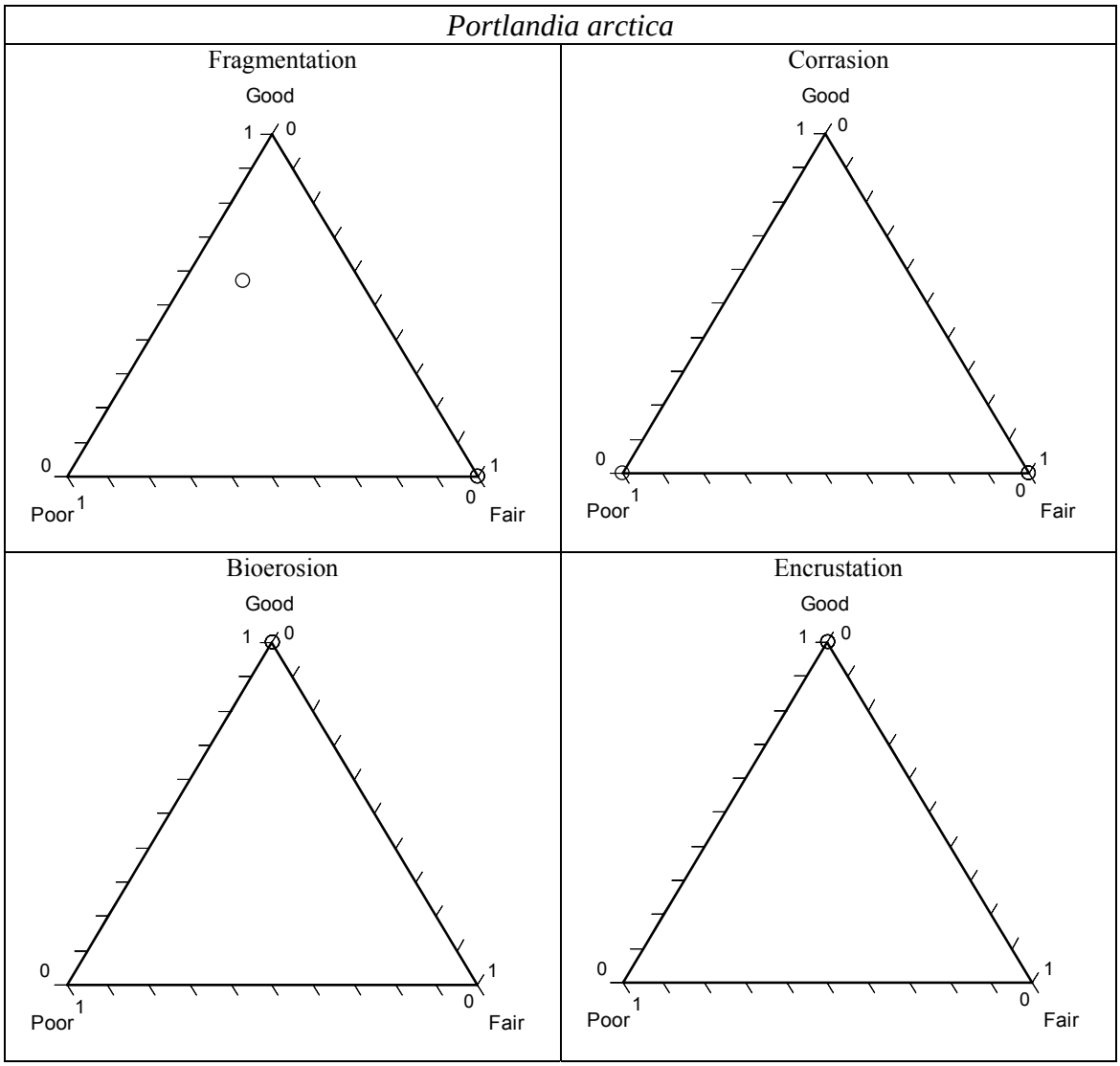


Figure 5.8 Ternary diagrams for *Portlandia arctica* recovered from Facies 4.

5.2.4 Valve Ratio and Valve Length

The degree of shell disarticulation was examined by comparison of right:left valve ratios and shell length distributions for four common bivalve taxa: *Astarte borealis*, *Hiatella arctica*, *Mya truncata* and *Serripes groenlandicus*. The null hypothesis (left to right valve ratio = 1:1) is rejected for five samples, which means significant disarticulation has been observed in these shell assemblages (Table 5.4). *Mya truncata*

exhibits the highest degree of disarticulation: the chi-square value (98.92) is much larger than the critical value (47.40) for the whole assemblages at the 5% significant level.

Table 5.4 The results of chi-square test of the ratio of left to right valves for four species (H_0: null hypothesis, α = significance level, df = degree of freedom)

Species name	*Hiatella arctica*	*Mya truncata*	*Astarte borealis*	*Serripes groenlandicus*	H_0: left to right valve ratio = 1:1
	χ^2	χ^2	χ^2	χ^2	Critical value for single sample = 3.84 (α = 0.05, df = 1),
ES-Sh2-0707	-	-	0.20	-	Not reject
ES-Sh3-0807	**4.26**	0.89	1.00	-	**Reject**
ES-Sh4-0807	3.00	0.24	0.33	1.00	Do not reject
ES-Sh5a-0807	0.67	0.89	0.17	1.00	Do not reject
ES-Sh5b-0807	0.33	0.67	0.01	1.00	Do not reject
ES-Sh6-0807	-	1.00	-	-	Do not reject
ES-Sh8-0802	-	-	-	-	-
ES-Sh9-0907	-	1.00	0.67	0.20	Do not reject
ES-Sh10-0907	-	-	-	-	-
ES-Sh17-0907	0.20	0.14	0.07	0.50	Do not reject
ES-Sh18-0907	-	-	-	-	-
ES-Sh19-0907	-	-	-	-	-
ES-Sh20-0907	-	1.00	-	-	Do not reject
ES-Sh21-0907	-	0.33	0.14	0.11	Do not reject
ES-Sh22-0907	-	-	-	1.80	Do not reject
ES-Sh23-0907	-	-	-	-	-
ES-Sh24-0907	-	-	-	-	-
ES-Sh25-1007	-	-	-	-	-
ES-Sh27-1207	0.42	0.59	0.10	1.56	Do not reject
ES-Sh28-1207	-	-	0.20	-	-
ES-Sh29-1207	0.08	0.26	1.60	-	Do not reject
ES-Sh30-1207	0.50	0.09	0.05	0.20	Do not reject
ES-Sh31-1207	0.06	-	0.20	0.33	Do not reject
ES-Sh32-1207	-	-	0.82	-	Do not reject
ES-Sh33-1207	0.33	0.33	1.00	-	Do not reject
MF-12-S-2998	0.33	1.00	0.01	-	Do not reject
MF-13-S-2998	1.00	0.47	-	-	Do not reject
MF-14-S-3098	-	2.48	-	-	Do not reject
MF-16-S-0198	0.33	-	-	-	Do not reject
MF-18-S-0298	1.00	-	0.01	-	Do not reject
MF-19-S-0298	-	-	-	0.20	Do not reject
MF-20-S-0398	0.20	0.33	-	3.00	Do not reject
MF-21-S-0498	-	-	-	-	-
MF-23-S-0598	1.00	1.00	0.36	-	Do not reject
MF-26A/S-0898	-	-	-	-	-
MF-26C/S-0898	-	-	-	-	-
MF-26D/S-0898	-	-	-	-	-
MF-26E/S-0898	-	-	-	-	-
MF-27-S-0998	0.00	0.43	0.02	0.16	Do not reject
MF-28-S-0998	3.27	0.25	2.31	-	Do not reject

MF-29-S-0998	0.58	0.01	0.14	0.14	Do not reject
ES-01-S-9402	**12.78**	**55.54**	**7.76**	1.67	**Reject**
ES-03-S-9404	-	**12.20**	-	0.33	**Reject**
ES-04A-S-9404	-	0.40	0.57	2.57	Do not reject
ES-04D-S-9404	-	1.29	0.17	0.02	Do not reject
ES-04E-S-9404	0.14	0.33	0.55	2.27	Do not reject
ES-04F-S-9404	1.29	**7.36**	1.18	0.16	**Reject**
ES-05-S-9405	2.31	0.20	2.00	1.00	Do not reject
ES-08-S-9405	-	-	0.14	-	Do not reject
ES-09-S-9406	0.86	0.08	1.60	2.00	Do not reject
ES-10-S-9407	0.16	0.67	-	-	Do not reject
ES-11-S-9408	-	1.00	-	-	Do not reject
ES-15-S-9418	0.03	0.82	-	-	Do not reject
ES-17-S-9421	**5.33**	**5.49**	**14.00**	-	**Reject**
ES-18-S-9421	0.01	0.14	0.83	1.00	Do not reject
Chi-square value of single species from 55 samples	**40.49**	**98.92**	38.22	22.23	
Critical value for species (α = 0.05)	40.11 (df = 27)	47.40 (df = 33)	43.77 (df = 30)	33.92 (df = 22)	
Null hypothesis: left to right valve ratio = 1:1	**Reject**	**Reject**	Do not reject	Do not reject	

"-": no data.

The data for shell length are summarized in Table 5.5. The populations of shells for *Hiatella arctica* and *Mya truncata* consist exclusively of large adult shells (length > 20 mm). The populations of shells for *Astarte borealis* consists of both adult and juvenile (length < 20 mm) shells.

The size-frequency distributions for twelve samples are presented in Figure 5.9. The shells with highest frequency value (mode) exhibit shell length greater than 20 mm except for three samples (ES-Sh8-0802, ES-04A-S-9404, ES-04E-S-9404). Juvenile shells are considerably represented in seven of the twelve samples which are recovered from Facies 2, 4, 5, 6, and 7. The great majority of shells in these samples are adult shells. The size-frequency distributions for most of the twelve samples are unimodal except for two samples from Facies 6 (ES-04A-S-9404) and Facies 7 (ES-Sh17-0907) each of which has obviously two modes for the distribution.

Table 5.5 Descriptive measures for valve size for three common species.

Descriptive Measures	*Hiatella arctica*	*Mya truncata*	*Astarte borealis*
For Samples			
Number of samples	26	23	37
Minimum valve length (mm)	28.4±6.1	35.3±8.6	15.9±7.5
Maximum valve length (mm)	37.5±5.5	46.2±6.0	32.1±8.8
For Facies			
Number of facies	6	5	6
Minimum valve length (mm)	24.2±5.6	25.2±7.0	8.9±3.9
Maximum valve length (mm)	42.7±4.8	54.1±5.1	42.5±4.4

5.2.5 Paleo-Guild Structure

Seven guilds are represented among the Bivalvia and Gastropoda recorded in the 55 shell samples: infaunal suspension-feeder, infaunal deposit-feeder, semi-infaunal suspension-feeder, epifaunal suspension-feeder, epifaunal predator, infaunal predator, and grazer (Table 5.6**)**. Semi-infaunal (endobyssate) suspension-feeders are those taxa, such as *Hiatella* and *Lyonsia*, whose body mass straddles the sediment-water interface.

Among the seven guilds, infaunal suspension-feeders dominate in the paleocommunities with a proportion of more than 60%, followed by semi-infaunal suspension-feeders with a proportion of almost 1/3. These two guilds together contribute more than 90% of 4616 individuals within the paleocommunities examined in this study. Infaunal deposit-feeders contribute only 2.34% of the total abundance. Of all 27 taxa identified in this study, these three infaunal guilds together contain 17 taxa whereas the other four guilds contain 10 taxa. Epifaunal suspension-feeders and infaunal predators are poorly preserved while epifaunal predators and grazers are poorly represented in shell samples.

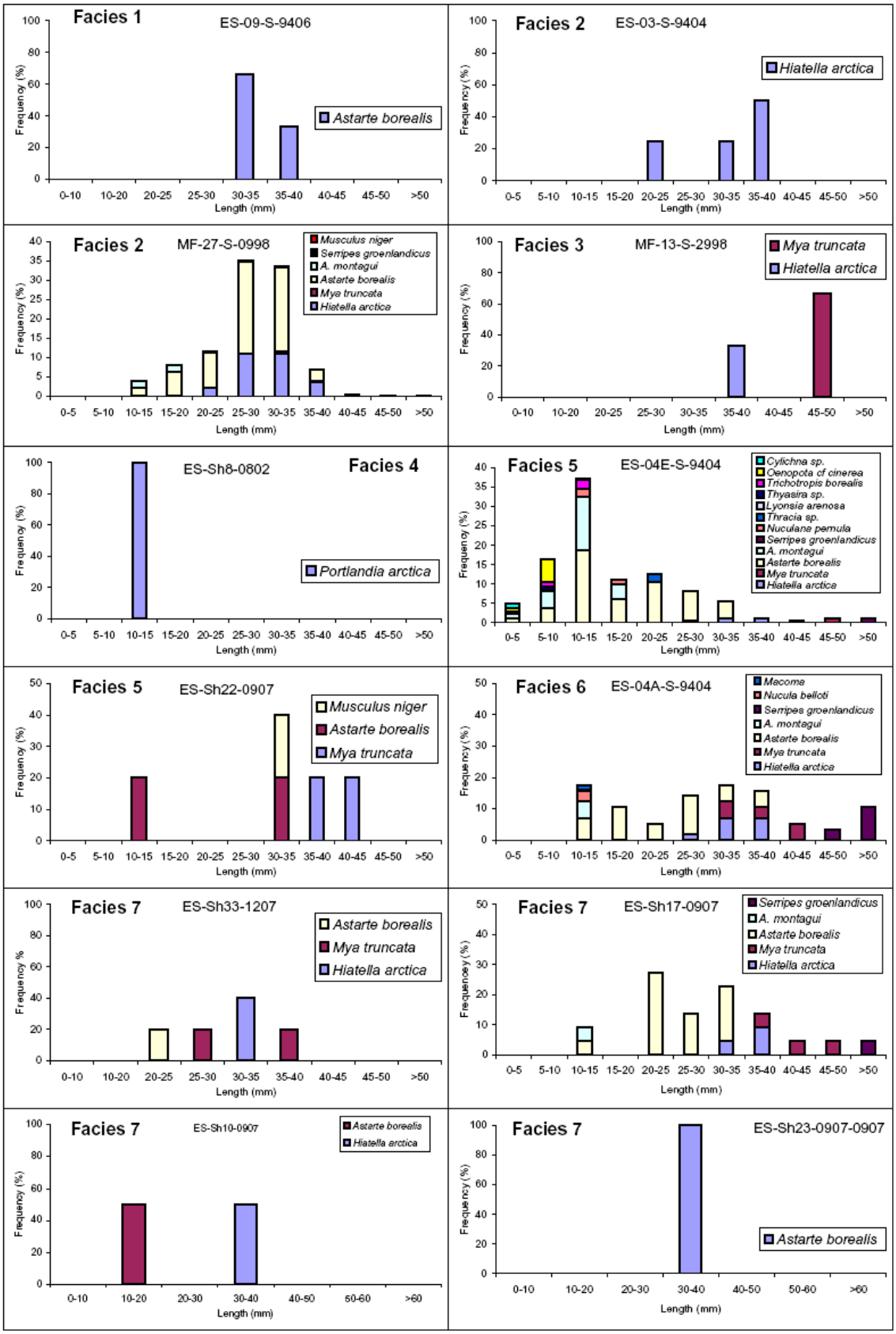


Figure 5.9 Size-frequency distributions for 12 samples represented in seven facies.

Table 5.6 Guild structure for Bivalvia and Gastropoda recorded in this study (R.A. = relative abundance).

	Guild	R. A. (%)	Taxa
1.	Infaunal suspension-feeder	63.71	*Astarte*, *Clinocardium*, *Serripes*, *Thracia*, *Pandora*, *Mya*
2.	Infaunal deposit-feeder	2.34	*Nucula*, *Nuculana*, *Portlandia*, *Macoma*, *Thyasira*
3.	Semi-infaunal (endobyssate) suspension-feeder	32.58	*Hiatella*, *Lyonsia*
4.	Epifaunal suspension-feeder	0.48	*Musculus*, *Trichotropis*
5.	Epifaunal predator	0.30	*Buccinum*, *Colus*, *Cylichna*
6.	Infaunal predator	0.52	*Oenopota*
7.	Grazer (spired)	0.06	*Margarites*

5.3 Depositional Environments and Taphofacies Analysis

Data related to taphonomic grade, right:left valve ratios, and shell length-frequency distributions have been collated for each of the seven different depositional environments represented in the study area (Table 5.7, 5.8 and 5.9). The shell length data for *Astarte*, *Hiatella* and *Mya* are illustrated separately to assess the impact of taphonomic processes on the shell assemblages associated with each of the sedimentary facies.

Shell samples from Facies 1 (diamicton) exhibit poor to fair preservation and a high degree of shell disarticulation. Shell size-frequency distributions are unimodal and left-skewed for *Hiatella* and *Astarte* shells. No complete *Mya* shells were observed in this group of samples.

Facies 2 (gravel and sand) contains samples that exhibit poor to fair preservation, and few or no articulated shells. Size-frequency distributions for the three infaunal

suspension-feeders, *Hiatella*, *Mya*, and *Astarte* are respectively little skewed, left-skewed, and right-skewed.

Facies 3 (interbbed silt and sand) contains samples that exhibit "poor-fair" preservation for *Hiatella* and *Mya* shells, and "fair" preservation for *Astarte* shells. No significant disarticulation occurred among these three taxa. Left-skewed size-frequency distributions for *Hiatella* and *Astarte* shells demonstrate that more small-sized shells accumulated than large shells.

Facies 4 (clay-silt-sand rhythmites) contains mainly *Portlandia arctica* shells except for a single *Hiatella* shell. The *Portlandia* shells exhibit poor to fair preservation. The number of shells in this group is insufficient to perform the chi-square test for valve ratios or examine valve size-frequency.

Facies 5 (pebbly sand and gravel with algal debris) contains samples that exhibit "fair" preservation of *Hiatella* shells, "poor-fair" preservation of *Mya* shells, and "fair" preservation of *Astarte* shells. No significant disarticulation occurred for most of the shells with the exception of *Mya*. The size-frequency distributions for *Hiatella* and *Astarte* shells are right-skewed, whereas the size-frequency distribution for *Mya* is left-skewed.

Facies 6 (pebbly silt with algal debris) contains samples that exhibit "fair" preservation for *Hiatella* shells and *Astarte* shells, and "poor to fair" preservation for *Mya* shells. No significant disarticulation was observed for any of the three species. The size-frequency distribution for *Astarte* shells is left-skewed, and for *Hiatella* or *Mya* is right-skewed.

Table 5.7 Taphonomic measures, chi-square tests of valve ratio, and size-frequency distribution of *Hiatella arctica* from seven different depositional environments.

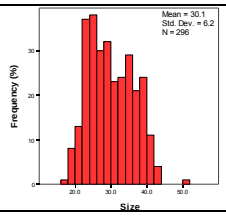
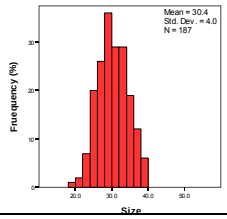
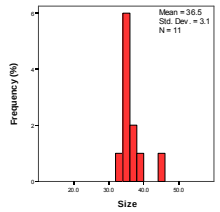
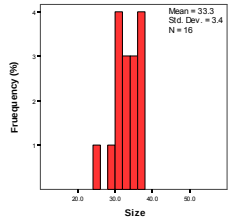
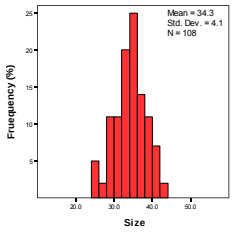
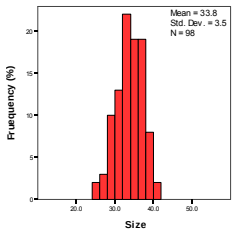
Depositional Environments	Taphonomic grade	H_0: left to right valve ratio = 1:1	Size-frequency			
			Mean (mm)	Mode (mm)	SD (mm)	Distribution
1. Glacial: diamicton	Poor	**Reject**	30.1	25.5	6.2	
2. Beaches: wave-washed glacial till; gravel	Poor to Fair	**Reject**	30.4	29.8	4.0	
3. Shallow marine: massive silt or interbedded with thin sand laminations	Poor to Fair	Do not reject	36.5	37.9	3.1	
4. Proglacial: rhythmically bedded / laminated silt and sand	-	-	-			-
5. Shallow marine or estuarine: pebbly sand and gravel with algal debris	Fair	Do not reject	33.3	25.8	3.4	
6. Shallow marine or estuarine: pebbly silt with algal debris	Fair	Do not reject	34.3	34.9	4.1	
7. Shallow marine or estuarine: interbedded silt and sand	Good to Fair	Do not reject	33.8	32.1	3.5	

Table 5.8 Taphonomic measures, chi-square tests of valve ratio, and size-frequency distribution of *Mya truncata* from seven different depositional environments.

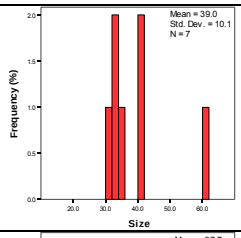
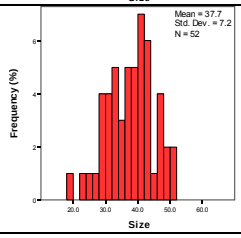
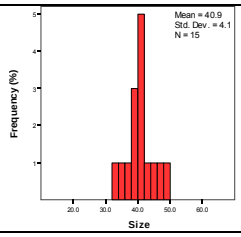
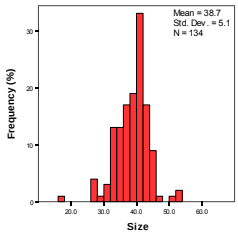
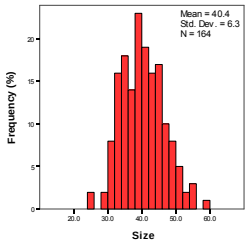
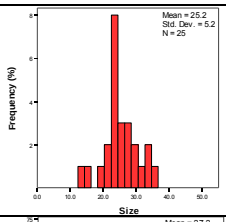
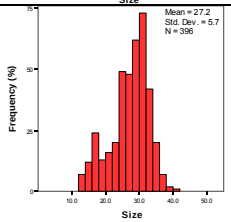
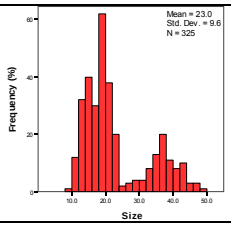
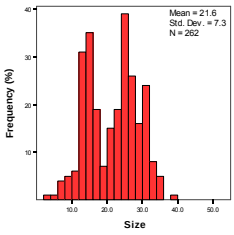
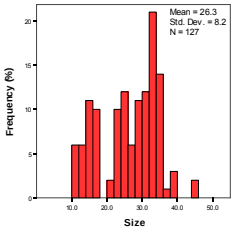
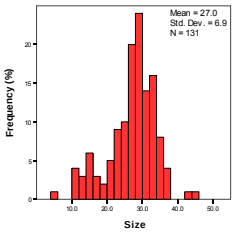
Depositional Environments	Taphonomic grade	H_0: left to right valve ratio = 1:1	Size-frequency			
			Mean (mm)	Mode (mm)	SD (mm)	Distribution
1. Glacial: diamicton	Poor	**Reject**	-	-	-	-
2. Beaches: wave-washed glacial till; gravel	Poor	**Reject**	39.0	31.2	10.1	
3. Shallow marine: massive silt or interbedded with thin sand laminations	Poor to Fair	Do not reject	37.7	33	7.2	
4. Proglacial: rhythmically bedded / laminated silt and sand	-	-	-	0		-
5. Shallow marine or estuarine: pebbly sand and gravel with algal debris	Poor to Fair	**Reject**	40.9	33.4	4.1	
6. Shallow marine or estuarine: pebbly silt with algal debris	Poor to Fair	Do not reject	38.7	40.3	5.1	
7. Shallow marine or estuarine: interbedded silt and sand	Poor to Fair	Do not reject	40.4	42.4	6.3	

Table 5.9 Taphonomic measures, chi-square tests of valve ratio, and size-frequency distribution of *Astarte borealis* from seven different depositional environments. (*: Multiple modes exist. The smallest value is shown.)

Depositional Environments	Taphonomic grade	H_0: left to right valve ratio = 1:1	Size-frequency			
			Mean (mm)	Mode* (mm)	SD (mm)	Distribution
1. Glacial: diamicton	Poor to Fair	**Reject**	25.2	23.2	5.2	
2. Beaches: wave-washed glacial till; gravel	Poor to Fair	Do not reject	27.2	31.0	5.7	
3. Shallow marine: massive silt or interbedded with thin sand laminations	Fair	Do not reject	23.0	19.0	9.6	
4. Proglacial: rhythmically bedded / laminated silt and sand	-	-	-	-	-	-
5. Shallow marine or estuarine: pebbly sand and gravel with algal debris	Fair	Do not reject	21.6	15.6	7.3	
6. Shallow marine or estuarine: pebbly silt with algal debris	Fair	Do not reject	26.3	28.2	8.2	
7. Shallow marine or estuarine: interbedded silt and sand	Fair to Good	Do not reject	27.0	26.2	6.9	

Facies 7 (interbedded silt and sand) contains samples that exhibit "fair to good" preservation of *Hiatella* and *Astarte* shells, and "poor to fair" preservation of *Mya* shells, without no significant disarticulation observed for any of the three taxa. Size-frequency distributions are unimodal without obvious skeweness for all of the three taxa.

5.3 Summary of Results

1. Bivalves (99.07%; n = 5018) dominate the fossil assemblages with respect to gastropods (0.93%; n = 47). Suspension feeders (96.78%; n = 4902) dominate the fossil assemblages with respect to feeding mode. The bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* are the most common species among the identified 27 taxa. Six associations and three taxa groups are recognized from cluster analysis and Multidimensional Scaling.

2. Most shells of the four common taxa either substantially or completely lose their luster with only a few shells slightly corroded or abraded, and exhibit little or no evidence of bioerosion or encrustation. *Astarte* exhibits a greater retention of shell luster relative to *Mya* and *Serripes*.

3. All shells from Facies 1 (diamicton) and some from Facies 2, 3, and 4 exhibit poor or fair preservation, whereas, shells from Facies 5, 6, and 7 contributes to fair or good preservation.

4. No significant asymmetry between right and left valve number occurred except for five of the 55 samples. *Mya truncata* exhibits the high degree of disarticulation compared to *Hiatella arctica*, *Astarte borealis*, and *Serripes groenlandicus*. The great

majority of shells in the assemblages are adult shells (length > 20 mm), except for some juvenile shells (length < 20 mm) for *Astarte borealis* in only a few samples.

5. The fossil assemblage was dominated by infaunal suspension-feeders and semi-infaunal (endobyssate) suspension-feeders evaluated by relative abundance, with infaunal deposit-feeders also well preserved.

CHAPTER 6 DISCUSSION

6.1 Species Composition and Ecological Characters

The 55 samples were collected from several different geomorphic environments: raised glaciomarine and estuarine sediments, and glacial tills. The species composition of a given shell assemblage represents the spatially and temporally averaged record of benthic ecosystems (Kowalewski *et al.*, 1994). The molluscs recorded in the fossil assemblages examined in this study typically inhabit shallow waters and are adapted to substrates ranging from rocky bottoms to unconsolidated sediments (Table 5.3). Bivalves are overwhelming more abundant than gastropod in the fossil assemblages. Most of the bivalves are mobile forms burrowing into the substrata. *Hiatella arctica* and *Lyonsia arenosa* live byssally attached as epifauna or partially buried as infauna. Only *Musculus* spp. is uniquely epifaunal in habit being attached to the substratum by byssal threads. Most of the gastropods live as vagrant predators except only for *Trichotropis* which is a suspension-feeder. Suspension-feeding organisms were preferentially preserved in the post-glacial sediments of Axel Heiberg Island. These patterns of macrofossil preservation corroborate observations of macrofossil preservation elsewhere in high arctic regions (Aitken, 1990; Lemmen *et al.*, 1994; Aitken and Bell, 1998; Simonarson *et al.*, 1998; Gordillo and Aitken, 2001).

The species composition of the molluscan associations described in Chapter 5 can be interpreted ecologically. Firstly, *Hiatella arctica*, *Mya* spp., *Astarte* spp., and *Serripes groenlandicus* all share the same ecological characteristics of infaunal habit and suspension feeding mode; whereas *Macoma* and *Portlandia* are infaunal deposit

feeders. Secondly, during the late glacial and early postglacial period of the Canadian high arctic, *Portlandia arctica* appears as the pioneer species that dominated in nearshore marine environments, occasionally associated with *Hiatella arctica* and *Mya truncata* (Lemmen *et al.*, 1994; Gordillo and Aitken, 2001). Later on other species, such as *Macoma calcarea* and *Astarte borealis*, are recorded in association with the former three species (Lemmen *et al.*, 1994; Gordillo and Aitken, 2001). The development of modern marine environments is characterized by the addition of *Serripes groenlandicus*, *Clinocardium ciliatum*, and *Buccinum* sp. as part of diverse mollusc associations during the late post-glacial period (Lemmen *et al.*, 1994; Gordillo and Aitken, 2001).

All of the molluscs examined in this study cohabit soft bottoms composed of silt and silty clay from the intertidal zone to depths of 50 meters or more. These nearshore environments are associated with polar or fjord water masses and influenced by sea ice and iceberg scouring. The range of salinity tolerated by these species varies from 15‰ to more than 32‰ with a common temperature range of -2°C to 10°C. Most of the species exhibit Arctic-Boreal and circumpolar distributions with geological ranges from the Miocene or Pleistocene to the Recent (Table 5.3).

6.2 Macrofaunal Associations

The result from cluster analysis on samples produced six unique associations. The associations are defined according to the species composition of each group as the *Portlandia* association (Group 1), the *Astarte* association (Group 2), the *Mya* association (Group 3), the *Hiatella-Mya* association (Group 4), the *Hiatella-Mya-Astarte-Serripes* association (Group 5A), and the *Hiatella-Mya-Astarte* association (Group 5B) (Table 5.2). The six groups recognized in the clustering analysis are similar

to the results of the MDS method (Figure 5.3). MDS defines five groups whose species composition is similar to that of the six groups recognized in the clustering analysis (Table 6.1). The only point (ES-Sh18-0907) that doesn't correspond is the single point from Group 4 that clusters with Group 1 in the MDS results. One obvious reason for the differences should be due to different distance measures used in the two methods. The composition of these associations is comparable to the composition of modern communities inhabiting nearshore environments in fjords and on the continental shelf of the eastern Canadian Arctic (Table 6.2) (Dale *et al.*, 1989; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993; Dyke *et al.*, 1996a; Gordillo and Aitken, 2001).

Table 6.1 Comparison of the results of cluster analysis and MDS in terms of the compositions of groups and corresponding facies.

Cluster Analysis	MDS	Facies
1. *Portlandia* association *Portlandia arctica*, *Astarte borealis*, *A. montagui*, *Hiatella arctica*	*Portlandia arctica*, *Serripes groenlandicus*, *Macoma loveni*	3, 4
2. *Astarte* association	The same	5, 6, 7
3. *Mya* association	The same	1, 2, 3
4. *Hiatella-Mya* association	The same	2, 4, 7
5A. *Hiatella-Mya-Astarte-Serripes* association	The same	1, 2, 3, 5, 6, 7
5B. *Hiatella-Mya-Astarte* association		

According to Figure 5.4 and Table 6.1, *Portlandia* association occurs in Facies 3 and Facies 4 which correspond to ice-proximal environments characterized by rapid retreat of sea ice margins, limiting marine primary production, variable salinities, and rapid clastic sedimentation in glacial meltwater. Syvitski *et al.* (1989) and Dyke *et al.* (1996a) also observed *Portlandia* association (dominated by *Portlandia arctica* alone) that is common in fine-grained, ice proximal glaciomarine sediments deposited at the

first stage of deglaciation. The diverse *Hiatella-Mya-Astarte-Serripes* association occurs in most facies except for Facies 4. This means glaciers reworked or disturbed diverse marine faunas. The six macrofaunal associations, therefore, do not distinctly correspond to the facies identified from the associated sediments in this study.

Table 6.2 Comparison of the species composition of fossil mollusc assemblages with modern arctic mollusc communities.

Communities	In shallow water (0-50 m)	In deep water in fiords (>50 m)	Source
Modern mollusc communities in the Canadian Arctic	*Astarte borealis* *Axinopsida orbiculata* *Buccinum hydrophanum* *Hiatella arctica* *Macoma calcarea* *Musculus discors* *Mya truncata* *Portlandia arctica* *Thyasira sp.*	*Axinopsida orbiculata* *Delectopecten greenlandicus* *Hiatella arctica* *Nucula belloti* *Nuculana pernula* *Portlandia arctica* *Yoldiella intermedia* *Yoldiella lenticula*	Dale *et al*., 1989; Dyke *et al*., 1996a; Syvitski *et al*., 1989; Aitken and Fournier, 1993
Fossil associations	***Portlandia* association**: *Portlandia arctica*, *Astarte borealis*, *A. montagui***,** *Hiatella arctica* ***Astarte* association**: *Astarte borealis*, *A. montagui*, *Nuculana pernula*, *Macoma calcarea*, *M. loveni*, *Hiatella arctica*, *Mya truncata*, *Serripes groenlandicus*, *Musculus niger*, *M. discor*, *Thracia myopsis*, *Thyasira* sp., *Lyonsia arenosa*, *Cylichna* sp., *Oenopota* c.f. *cinerea*, *Trichotropis borealis* ***Mya* association**: *Mya truncata*, *Serripes groenlandicus*, *Hiatella arctica* ***Hiatella-Mya* association**: *Hiatella arctica, Mya truncata*, *Serripes groenlandicus*, *Astarte borealis*, *A. montagui*, *Macoma calcarea*, *M. loveni* ***Hiatella-Mya-Astarte-Serripes* association**: *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, *A. montagui*, *Serripes groenlandicus*, *Pandora glacialis*, *Musculus niger*, *M. corrugatus*, *Buccinum totteni*, *B. finmarkianum*, *Nucula belloti*, *Thyasira* sp., *Clinocardium ciliatum*, *Margarites olivacens*, *Macoma calcarea*, *M. loveni*, *M. moesta*, *Nuculana pernula*, *Thracia myopsis*, *Colus c.f. togatus* ***Hiatella-Mya-Astarte* association**: *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, *A. montagui*, *Musculus niger*, *Thracia* sp., *Serripes groenlandicus*, *Clinocardium ciliatum*, *Macoma calcarea*, *Portlandia arctica*, *Nuculana pernula*, *Macoma calcarea*		This study

Three distinct clusters of taxa emerge from the MDS analysis of the eleven most common taxa represented in the shell assemblages (Figure 5.2): a group of deposit-

feeding taxa, *Portlandia arctica*, *Macoma calcarea*, *M. loveni*, *M. moesta*, and *Nuculana pernula*; a group of suspension-feeding taxa, *Hiatella arctica, Mya truncata, M. pseudoarenaria, Astarte borealis, A. montagui, and Serripes groenlandicus*; and a group of rare taxa. Dimension 2 highlights the feeding mode of the various taxa. The deposit-feeding taxa are present in fewer samples than the suspension-feeding taxa but in more samples than the rare taxa, so that dimension 1 highlights variations in the relative abundance of the various taxa represented in the entire shell collection.

6.3 The Origin of Taphonomic Patterns

The biological (bioerosion, encrustation) and mechanical (fragmentation, corrasion) modifications vary among the taxa represented in the fossil assemblages and result from different processes operating at different stages in the taphonomic history of skeletonized remains.

6.3.1 Mechanical variables.

The degree of shell fragmentation can provide information about the energy of depositional environments, as well as the effects of ice scouring in nearshore environments and the development of permafrost in raised marine sediments (Shabica, 1971; Cadee, 1999). The four most common taxa represented in the fossil assemblages, *Hiatella*, *Mya*, *Astarte* and *Serripes*, exhibit substantial differences in the degree of fragmentation: *Serripes* exhibits the greatest degree of fragmentation, followed by *Hiatella*, *Mya*, and *Astarte* with the lowest degree of fragmentation. These four species commonly cohabit nearshore environments and have experienced similar post-mortem environmental histories, so that differences in shell preservation among these species indicate that the shells of *Serripes*, *Hiatella* and *Mya* are more easily damaged than the

shells of *Astarte*. Gordillo and Aitken (2001) observed a similar pattern among the shell collections from Prince of Wales Island and areas further north that *Astarte borealis* exhibited the highest resistance to breakage; *Hiatella arctica* obtained intermediate level; and *Mya truncata* exhibited the lowest resistance. For *Hiatella*, the shells mostly fragmented characterize Facies 1 (diamicton) and Facies 2 (beach ridges) where high energy and glacier or wave effects are expected; shells exhibiting little to no fragmentation are mostly from Facies 5 (pebbly sand and gravel with algal debris) and Facies 6 (pebbly silt and gravel with algal debris) where lower energy associated with shallow marine environments are expected; and Facies 3 (glaciomarine) and Facies 7 (interbedded silt and sand) consists of mixed shells that are extensively fragmented or well to moderately preserved, which indicate the combined effects of glacier, wave, and sea ice scouring in nearshore marine environments. For the small, thin shells of *Portlandia arctica*, Gordillo and Aitken (2000) argued that they are more susceptible to postmortem degradation relative to larger and/or thick-shelled *Mya*, *Hiatella*, and *Astarte*. The moderately fragmented *Portlandia* shells recovered from Facies 4, therefore, may or may not correspond to environments with high energy.

The loss of luster that obscures shell ornamentation and contributes to the chalky appearance of shells results from abrasion and chemical dissolution (corrosion). Intense corrasion can be attributed to abrasion by coarse substrates and/or sea ice in high-energy nearshore environments or high solubility of carbonate shells in acidic solutions within the TAZ (Driscoll and Weltin, 1973; Flessa and Brown, 1983; Parsons and Brett, 1991). Luster is “very rarely preserved in the fossil record because the post-burial processes associated with diagenesis and outcrop weathering usually result in a total

loss of shell luster" (Kowalewski *et al.*, 1994). The loss of shell luster among all samples of *Hiatella*, *Mya*, *Astarte*, *Serripes* and *Portlandia* suggests that this taphonomic feature is not indicative of the energy of depositional environment but probably corresponds to the long-term taphonomic processes associated with the enclosing sediments.

6.3.2 Biological variables

Bioerosion and encrustation are directly associated with the activities of bioeroding and encrusting organisms during and after the death of the host organisms (Neumann, 1966; Perkins and Tsentas, 1976; Parsons and Brett, 1991; Kowalewski *et al.*, 1994). The general absence of strongly bioeroded or encrusted shells among samples of *Hiatella*, *Mya*, *Astarte* and *Serripes* and the absence of bioeroded or encrusted *Portlandia* shells suggests rapid burial of the shells with only limited exposure on the sediment surface, or the absence of grazing, boring or encrusting taxa in the environment (Parsons and Brett, 1991). This result is consistent with infaunal habit of most of the taxa represented in the shell assemblages.

6.4 Supplementary Analyses – Valve Ratios and Valve Size

6.4.1 Left-Right Valve Ratios

Disarticulation is greatest where sedimentation rate is low and shells are continually reworked by normal wave disturbance and sea ice scouring (Speyer and Brett, 1988a). Long-term surface exposure of shells in environments not significantly affected by current energy also lead to considerable disarticulation but this situation does not indicate substantial transportation of shells (Speyer and Brett, 1988a). The degree of shell disarticulation for the four most common taxa represented in the shell assemblages

(*Astarte*, *Hiatella*, *Mya*, *Serripes*) is generally low with the exception of five samples (ES-Sh3-0807, ES-01-S-9402, ES-03-S-9404, ES-17-S-9421) that are associated with diamicton and raised beach ridges (wave-washed glacial till) where the shells are expected to experience a considerable degree of reworking by glaciers, waves, and sea ice. A single sample (ES-04F-S-9404) is associated with a high energy estuarine environment characterized by the deposition of pebbly sand and gravel with algal debris. This highly reworked shell assemblage bears evidence of disturbance by a combination of fluvial and marine processes. The lack of disarticulation in the other samples most likely reflects high sedimentation rates and rapid burial in nearshore environments, especially those from glaciomarine silts (Facies 3 and 4) and estuarine deposits (Facies 6 and 7), as indicated by as the preponderance of paired valves. This means that most of our samples are not substantially transported nor significantly reworked.

Among the samples highlighted above, *Mya truncata* is distinguished from the other three taxa (*Astarte*, *Hiatella*, and *Serripes*) by a high degree of shell disarticulation. Frey and Henderson (1987) argued that during the shell-sorting process, left and right valves tend to be rotated and transported differently by wave-generated currents. They also noted that valves of large species are separated more efficiently than valves of small species because the latter are more easily transported. It is evident that left and right valves of *Mya truncata* in this study are more susceptible to wave effects than those of other species due to their larger size and greater mass.

6.4.2 Valve Size and Size-Frequency Distributions

The size ranges for *Hiatella arctica*, *Mya truncata* and *Astarte borealis* indicate that more juvenile shells of *Astarte borealis* are represented in the mollusc assemblages than

those of *Hiatella arctica* and *Mya truncata*. Small shells are more easily fragmented or dissolved than larger shells. The relatively narrow ranges of *Hiatella* and *Mya* may be related to the species relatively poor resistance to shell breakage through time. Gordillo and Aitken (2001) observed a similar pattern for *Mya truncata* from Prince of Wales Island.

The size-frequency distributions for twelve samples indicate that the great majority of shells in these samples are adult shells. The juvenile shells represented in seven of the twelve samples mostly consist of juvenile *Astarte borealis*, and small species such as *Astarte montagui*, *Portlandia arctica*, *Nuculana pernula*, *Lyonsia arenosa*, *Thyasira* sp., *Oenopota* sp., and *Cylichna* sp. These diverse species, characterized by normally small shells and relatively poor resistance to breakage, are considerably represented in Facies 2, 4, 5, 6, 7, which indicates that these assemblages corresponds to the evidence of no transportation or exposure on the sea floor for any length of time.

Two samples (ES-04A-S-9404 from Facies 6, ES-Sh17-0907 from Facies 7) exhibit bimodal size-frequency distribution among the twelve samples analyzed in this study. According to Figure 5.7, the two modes of frequency values in these two samples correspond to the two modes of *Astarte borealis* shells represented in these samples. Size-selective taphonomic processes are important in determining the shape of the distributions. "Highly positively, moderately positively, and negatively skewed distributions primarily demonstrate the relative effects of size-selective taphonomy and the temporal pattern of larval settlement, and the size-frequency distribution of shells is usually unimodal if shells are from the death of a single cohort" (Cummins *et al*., 1986: p.512). There is no evidence of significant shell transportation, thus the bimodal

distribution of *Astarte borealis* shells may suggest that a catastrophic event might influence the preservation of the size structure of a living population with no evidence of physical transportation, or a large input pulse with a size-distribution different from that already present in the death assemblage might insert a secondary mode into the size-frequency distribution (Cummins *et al.*, 1986).

6.5 Taphofacies Analysis

Four taphofacies are distinguished in this study on the basis of cluster analysis of four taphonomic variables (fragmentation, corrasion, bioerosion, and encrustation) (Figure 5.2). The degree to which a shell is fragmented, corraded, bioeroded, or encrusted provides important information regarding environmental energy, sedimentation rates, and the degree of surface exposure. Of these, "the duration of surface exposure is clearly paramount and influences the relative effects of all other destructive agents" (Speyer and Brett, 1988: p. 254). The characteristics of the four taphofacies are discussed briefly below.

Taphofacies I (Group 1): poor preservation based on the highest degree of fragmentation, high to intermediate degrees of corrasion, and little or no bioerosion and encrustation. Among the seven depositional environments, all of the samples from Facies 1 (glacial) and some samples from the Facies 2 (beaches), Facies 3 (shallow marine), and Facies 4 (proglacial) depositional environments are included in Group 1. Facies 1 and 2 reflect high energy environments that contribute to the high degrees of fragmentation and corrasion. Facies 3 refers to lower energy offshore muds characterized by low rates of sedimentation with the potential for prolonged exposure of exhumed shells on the seafloor as these sediments emerge above sea level. Furthermore,

permafrost aggradation in these raised marine silts could crush shells. Shells in these three facies can be highly fragmented and corraded. Facies 4, however, exhibit a considerable degree of fragmentation. It is possible that crushing of these small shells is related to permafrost aggradation following emergence of these sediments above sea level.

Taphofacies II (Group 2A): fair preservation with intermediate scores for all of the four taphonomic features. The four samples were all recovered from Facies 7 associated with rapid sedimentation in nearshore environments. This depositional environment should favour rapid burial and excellent shell preservation. There is no evidence of transportation based on left and right valve ratios for these samples, which means these shells was probably crushed after burial by postmortem effects such as sea ice scouring or permafrost aggradation.

Taphofacies III (Group 2B): fair to good preservation with little or no fragmentation, intermediate corrasion, and little or no bioerosion and encrustation. Two distinct samples (ES-Sh10-0907, ES-Sh23-0907) from Facies 7 exhibit good preservation. The shell samples were recovered from shallow marine or estuarine (Facies 5, 6 and 7) depositional environments. The excellent shell preservation is consistent with the high rates of sedimentation in these nearshore environments.

Taphofacies IV (Group 2C): fair preservation based on a single sample (ES-Sh8-0802) recovered from Facies 4 (proglacial). This sample exhibits a high score for corrasion but a low score for fragmentation, and no evidence for bioerosion and encrustation. Though high rates of sedimentation in Facies 4 are expected, shells recovered from these sediments can be considerably fragmented and highly

abraded/corroded by exhumation on the seafloor or permafrost aggradation after emergence of the sediments.

The differences between these four taphofacies represent four different environmental conditions within the study area, which suggest that environmental energy and potential exposure time changed significantly during the periods before burial and after burial. The relationship between taphofacies and depositional environments (facies) in the study area is summarized in Table 6.3.

Table 6.3 Characteristics of taphofacies and corresponding facies recognized in this study.

Taphofacies	Grade of Taphonomic features	Preservation pattern	Taxa preserved	Facies
I	fragmentation: "poor" corrasion: "poor-fair" bioerosion: "fair-good" encrustation: "fair-good"	Poor	*Portlandia arctica, Astarte borealis, A. montagui, Clinocardium ciliatum, Serripes groenlandicus, Macoma calcarea, Mya truncata, Hiatella arctica*	1, 2, 3, 4
II	fragmentation: "fair" corrasion: "fair" bioerosion: "fair" encrustation: "fair"	Fair	*Astarte borealis, Serripes groenlandicus, Macoma loveni, Mya truncata, Hiatella arctica*	7
III	fragmentation: "fair-good" corrasion: "fair" bioerosion: "fair-good" encrustation: "fair-good"	Fair-Good	All of the 27 species identified (see Table 5.2)	5, 6, 7
IV	fragmentation: "fair" corrasion: "poor" bioerosion: "good" encrustation: "good"	Fair	*Portlandia arctica*	4

The action of sea ice can also effect shell preservation directly (Shabica, 1971; Cadee, 1999). Shell disarticulation and fragmentation can result from sea ice scouring of the seafloor and the development of permafrost in raised marine sediments. Bibeau *et al.* (2005) analyzed the molluscs from Resolute Bay, Canada to evaluate post-mortem modifications of mollusc shells in sea ice-scoured seafloor sediments. According to

their observations, severe fragmentation (90% of the shell material) occurred in nearshore environments at depth less than 50 meters. Post-mortem surface alteration recorded as chalky and pitted textures were observed on more than 90% of the specimens, and a significant proportion of the shells show extensive surface corrosion.

6.6 Paleoecology

6.6.1 Introduction

Molluscan paleoecology in the Canadian Arctic Archipelago has been examined by Mode (1985), Dyke *et al.* (1996a), Aitken and Bell (1998), Gordillo and Aitken (2000), and Gordillo and Aitken (2001). Considerable attention has been given to the fossil marine molluscs from the Arctic region in recent decades in that molluscs are the most common macrofossils observed in Late Quaternary raised marine sediments from North America and Greenland (Gordillo and Aitken, 2001). Despite the obvious bias in preservation (i.e. loss of soft bodies, postmortem taphonomic processes), macrofossil assemblages record useful information on the life habits and habitats of the arctic marine benthic communities from which they are derived (Aitken, 1990). The results of taxonomic and taphonomic analysis in Chapter 5 indicate that 1) the fossil assemblages did not experience significant transportation, and 2) the species composition of the fossil assemblages are comparable to that of modern benthic mollusc communities. Based on these observations, the ecological information recorded in this study is critical to the reconstruction of ancient marine benthic communities, especially in late Pleistocene-Holocene glaciomarine environments.

6.6.2 Trophic Relationships

Based on the results of guild analysis and the ecology of the identified molluscs described previously, a general reconstruction of probable predator-prey interactions in Late Quaternary marine molluscan communities is illustrated in Figure 6.1. Due to the taphonomic bias in fossil preservation, soft-bodied taxa which are numerically abundant (Aitken, 1990), are absent as body fossils in the fossil record. Most carnivores at higher trophic levels, therefore, cannot be incorporated into our model.

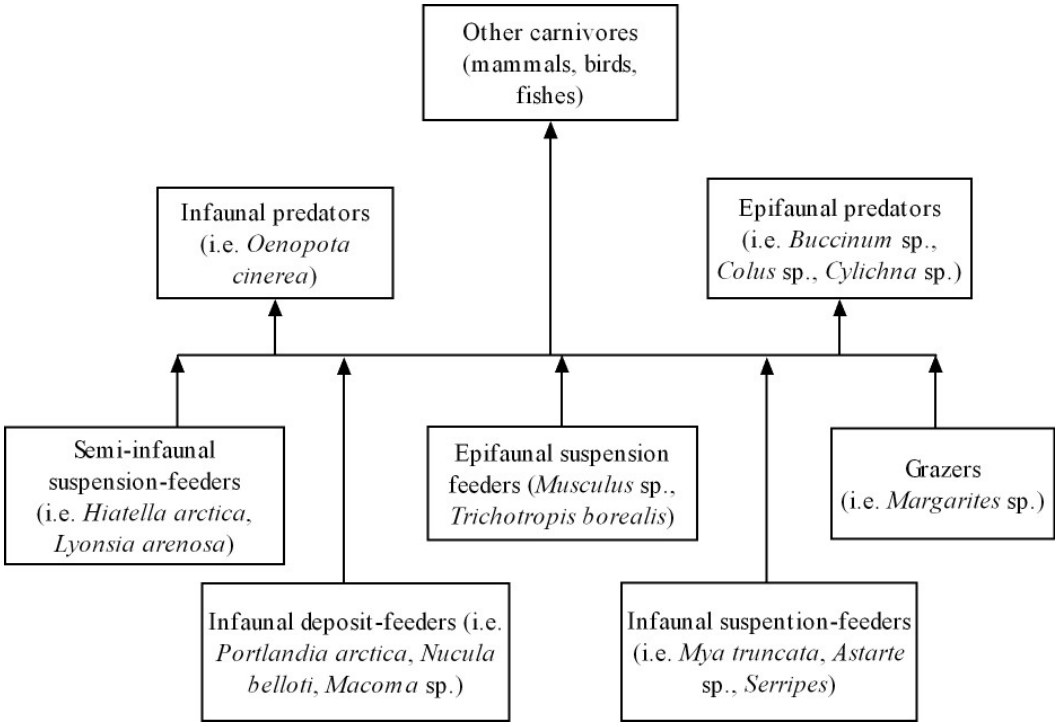


Figure 6.1 Trophic relationships for molluscs preserved in the fossil marine mollusc assemblages from Axel Heiberg Island. The arrows describe energy flowing between trophic levels.

6.6.3 Faunal Characterization

The description of the faunal composition and relative abundances of taxa is presented in Chapter 5 (also refer to Table 5.2 and 5.3). Twenty-seven species (20 bivalves, 7 gastropods) are represented in 55 samples. Each species presently inhabits

within the Canadian Arctic Archipelago, except for *Mya pseudoarenaria*. *Hiatella arctica* (32.5%), *Mya truncata* (23.2%), *Astarte borealis* (26.8%), and *Serripes groenlandicus* (9.5%) are the most common species represented in the fossil collections, which together represent 92.0% of the total fauna. Many studies have compared the species composition of fossil assemblages and modern benthic mollusc communities and concluded that habitat or substratum type could be inferred from the relative abundances of the species present in fossil assemblages (Kowalewski *et al.*, 1994; Dyke *et al.*, 1996a; Kidwell and Flessa, 1996; Staff and Powell, 1999; Gordillo and Aitken, 2000; Zuschin and Stanton, 2002). The samples examined for this study record the dominance of infaunal suspension-feeding bivalves (i.e., *Astarte*, *Clinocardium*, *Hiatella*, *Mya*, *Macoma*, *Serripes*, and *Thracia*) that are most abundant on sandy-clay or clay sediments typically occurring in nearshore environments less than 50 meters. This observation is consistent with the result of the paleoecological study of fossil mollusc assemblages from the central Canadian Archipelago by Gordillo and Aitken (2000). The dominance of bivalves (99.07%; n = 5018) with respect to gastropods (0.93%; n = 47) reflects a time-averaged record of the fossil assemblages inhabiting high latitude nearshore environments (Ellis, 1960; Thomsen and Vorren, 1986; Kowalewski *et al.*, 1994; Gordillo and Aitken, 2000).

The dominance of suspension feeders (96.78%; n = 4902) was described previously in this chapter and Chapter 5. Deposit feeders, carnivores, and browsers represent 2.41%, 0.75%, and 0.06% respectively in the macrofossil assemblages. Suspension-feeding organisms are more abundant on softground substrates (i.e. as infauna) characterized by low to moderate rates of clastic sedimentation, and firmground

substrates (i.e. as epifauna) characterized by low clastic sedimentation rates, ice scouring and erosion by currents (Dale *et al.*, 1989; Aitken and Fouriner, 1993).

The relative abundance of trophic groups in this study is consistent with the result of several studies of fossil mollusc assemblages (Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000). These authors observed that the trophic composition of paleocommunities is as follows: suspension-feeders > deposit feeders > carnivores > browsers, due to "different initial abundances between trophic groups, and differences in the preservation related to mobility and the nature of mineralized body parts" (Gordillo and Aitken, 2000: p. 305). It is clear that suspension feeders are preferentially preserved in the sediments of high arctic regions (see Aitken, 1990; Gordillo and Aitken, 2001). Species compositional fidelity can be significantly affected by skeletal modification initialized by sea-ice scouring in shallow Arctic marine environments (Bibeau *et al.*, 2005). Death assemblages within scours are negatively related to live assemblages, whereas death assemblages outside scours are high related to live assemblages, with regard to the fidelity of diversity and relative abundance data (Bibeau *et al.*, 2005).

6.6.4 Comparison with Modern Arctic Mollusc Communities

A comparison of the species composition of different benthic mollusc communities inhabiting high latitude fiords and shallow marine environments is presented in Table 6.4. In other studies listed in Table 7.3, more than 50% of the modern mollusc fauna is represented in the fossil faunas, including the same common taxa - *Astarte borealis*, *Hiatella arctica*, and *Mya truncata*. The large relative abundance of *Mya truncata* in the fossil assemblages is distinguished from its low relative abundance in the modern

faunas. This probably reflects the method of sampling modern benthos in that benthic trawls and grab samplers underestimate the presence of deeply buried (>5 cm depth) infaunal organisms, such as *Mya truncata* (Thomsen and Vorren, 1986; Gordillo and Aitken, 2000).

The relatively low abundance and/or absence of the taxa, *Nucula*, *Portlandia*, *Thyasira*, *Thracia*, *Bathyarca glacialis* and *Axinopsida orbiculata*, in the macrofossil assemblages may be attributed to a variety of biostratinomic processes. Small, thin shells (i.e. shells of *Portlandia*, *Thyasira*, *Nucula*) make them more susceptible to postmortem solution and fragmentation than larger and/or thicker shells (i.e. shells of *Mya*, *Hiatella*, and *Astarte*) (Dyke *et al.*, 1996a; Gordillo and Aitken, 2000). For example, the low relative abundance of *Portlandia* preserved in proglacial environments (Facies 4) associated with moderate degree of fragmentation. The absence of *Portlandia*, *Thyasira*, and *Nucula* in the fossil record may point to their relative rarity in the modern fauna. For example, Aitken and Gilbert (1996) examined the molluscs from Expedition Fjord and observed that *Thyasira gouldi*, *Nucula belloti* occur commonly and in low abundance with a *Portlandia-Hiatella* association in the inner and middle fjord. The gastropod taxa *Colus*, *Buccinum*, and *Margarites* are widely distributed in the Canadian Arctic and Greenland (Macpherson, 1971; Thomson *et al.*, 1986), but always occur in low abundance. Gordillo and Aitken (2000) noted that the possible reasons of the low relative abundance and/or absence of these taxa in fossil assemblages are their low abundance in modern benthic mollusc communities.

Table 6.4 Faunal composition of different mollusc communities from the Arctic region indicating taxa in common with fossil assemblages in this study (The abundance for common species are bolded).

Locality	Axel Heiberg Island	Axel Heiberg Island	Expedition Fiord	McBeth and Itirbilung Fiords	Cambridge Fiord
(region)	(Canadian Arctic)	(Canadian Arctic)	(Canadian Arctic)	(Baffin Island)	(Baffin Island)
Source of Data	This study	Gordillo and Aitken (2000)	Aitken and Gilbert (1996)	Aitken and Fournier (1993)	Syvitski, *et al*. (1989)
Source of Sample	Fossil Macrofauna		Modern Community		
Sampling method	Trowel	Trowel	Dredge	Grab	Grab
Abundance	Individual %	Relative abund.	Abund. × sample	Individual %	Individual %
Depth			4-80 m	0-50 m	19-750 m
Taxa					
Astarte borealis	**26.84** (1239)	**27.18**	**12.88**	-	4.60
Astarte montagui	3.75 (173)	-	-	-	**17.5**
Buccinum spp.	0.19 (9)	0.36	-	-	-
Clinocardium ciliatum	0.06 (3)	-	0.95	-	-
Colus sp.	0.06 (3)	0.27	-	-	-
Cylichna sp.	0.04 (2)	0.18	4.85	-	-
Hiatella arctica	**32.50** (1500)	**35.70**	3.66	**11.05**	-
Lyonsia arenosa	0.09 (4)	0.27	-	-	-
Macoma calcarea	0.71 (33)	0.18	0.71	1.92	6.53
Margarites sp.	0.06 (3)	0.27	-	-	-
Musculus niger	0.24 (11)	0.62	-	4.38 (1)	2.07 (2)
M.corrugatus	0.11 (5)	-	-	-	-
M. loveni	0.06 (3)	-	-	-	-
Mya pseudoarenaria	0.15 (7)	-	-	-	-
Mya truncata	**23.20** (1071)	**21.31**	0.47	1.05	-
Nucula belloti	0.02 (1)	-	-	0.5	6.53
Nuculana pernula	0.30 (14)	0.44	0.36	-	-
Oenopota sp.	0.52 (24)	2.13	0.59	-	-
Pandora glacialis	0.04 (2)	-	-	-	-
Portlandia arctica	1.19 (55)	-	**10.4**	**75.96**	1.04
Serripes groenlandicus	9.47 (437)	9.68	-	-	-
Thracia spp.	0.19 (9)	0.36	0.59	-	-
Thyasira sp.	0.04 (2)	-	7.21	-	-
Trichotropis borealis	0.13 (6)	0.53	3.19	-	-
Not shared taxa with fossil assemblages in this study	-	Minor taxa (0.52)	*Astarte warhami* (40.9) *Yoldiella lenticula* (4.61) Minor taxa (5.91)	*Axinopsida orbiculata* (5.1)	*Yoldiella* sp. (36.94) *Bathyarca glacialis* (11.87) *Axinopsida orbiculata* (11.87) Minor taxa (1.04)
Total number of taxa	24	26	21	11	12
Number of taxa in common	-	15 (57.7 %)	12 (57.14 %)	6 (54.5 %)	6 (50 %)
Abundance of taxa in common	-	99.48 %	45.86 %	94.91 %	36.2 %
Total number of specimens	4616 (individual)	1126	846	-	-

(1): *Musculus discor*
(2): *Musculus* sp.

For example, *Buccinum* sp. represented 0.4% of relative abundance in shallow water habitats in northwestern Baffin Island fiords recorded by bottom photographs (Aitken and Fouriner, 1993) but was not recorded in benthic trawl samples from Expedition Fiord, Axel Heiberg Island (Aitken and Gilbert, 1996). In macrofossil assemblages, the lower preservation potential of gastropods relative to infaunal bivalves may also contribute the lower abundance of these taxa.

Mya pseudoarenaria is the only species that is absent from modern benthic mollusc faunas in the High Arctic. It can be found in the low arctic presently inhabiting shallow water (2-30 m depth) in eastern Hudson Bay, but was more widespread in early postglacial time (Dyke *et al.*, 1996a). This species is the only mollusc in Canadian waters that appears to be approaching global extinction (Lubinsky, 1980; Dyke *et al.*, 1996a). The research on fossil *Mya pseudoarenaria* by Dyke *et al*. (1996a) suggested that 1) the distribution of this species was probably circumpolar until the late Pleistocene to late Holocene (i.e. 3.5 ka BP); 2) it did not survive in the Arctic Ocean through the last glacial maximum; and 3) its relict area continues to shrink due to shoaling and lowering salinities in shallow inshore zones. Based on these arguments, I suspect the fossil assemblages containing *Mya pseudoarenaria* are early to middle Holocene in age.

6.7 Postglacial Environments

6.7.1 Characteristics of Depositional Environments

The characteristics of the seven depositional environments are distinct from each other based on the differences in the sedimentology, and the species composition and mode of preservation of the fossil assemblages as summarized in Table 6.5.

Table 6.5 Characteristics of seven depositional environments in terms of lithofacies, taphonomy, and faunal composition recorded in this study.

Depositional environment (elevation range)		Taphonomy		Fossil macrofauna	Environmental conditions
		Taphonomic grade	Significant disarticulation		
1	Glacial: diamicton	fragmentation: poor corrasion: poor bioerosion: fair-good encrustation: fair-good	Yes	*Hiatella, Mya, Astarte, Serripes* (*Hiatella-Mya-Astarte-Serripes* association)	highest energy, rapid sedimentation
2	Beaches: wave-washed glacial till; gravel	fragmentation: poor-fair corrasion: poor bioerosion: fair-good encrustation: fair-good	Yes	*Hiatella, Mya, Astarte* (*Hiatella-Mya-Astarte* association)	high energy, rapid sedimentation
3	Shallow marine: massive silt or interbedded with thin sand laminations	fragmentation: fair corrasion: poor-fair bioerosion: fair-good encrustation: fair	No	*Hiatella, Mya, Astarte, Serripes, Macoma, Portlandia* (*Hiatella-Mya-Astarte-Serripes* association)	moderate energy, moderate sedimentation
4	Proglacial: rhythmically bedded / laminated silt and sand	fragmentation: poor-fair corrasion: poor-fair bioerosion: good encrustation: good	No	*Portlandia arctica*, *Hiatella arctica* (*Portlandia* association)	high/moderate energy, rapid sedimentation
5	Shallow marine or estuarine: pebbly sand and gravel with algal debris	fragmentation: fair corrasion: fair bioerosion: fair-good encrustation: fair-good	Yes	diverse bivalves and gastropods (*Hiatella-Mya-Astarte-Serripes* association)	moderate energy, moderate sedimentation
6	Shallow marine or estuarine: pebbly silt with algal debris	fragmentation: fair-good corrasion: fair bioerosion: fair-good encrustation: fair-good	No	infaunal suspension/deposit, epifaunal suspension bivalves (*Hiatella-Mya-Astarte-Serripes* association)	low energy, low sedimentation rate
7	Shallow marine or estuarine: interbedded silt and sand	fragmentation: fair-good corrasion: poor-fair bioerosion: fair-good encrustation: fair-good	No	diverse bivalves and gastropods; *Mya pseudoarenaria* included (*Hiatella-Mya-Astarte* association)	low energy, low sedimentation rate

The six macrofaunal associations identified from statistical analysis do not exhibit a precise correspondence to the seven sedimentary facies with the exception of the *Portlandia* association that is associated uniquely with Facies 4 (Table 6.5). The

Hiatella-Mya-Astarte-Serripes association dominated the Arctic benthic fauna before the Last Glacial Maximum and is recorded from diamictons (Facies 1), deposited as glaciers advanced across the study area. Samples from Facies 2 are dominated by species from the *Hiatella-Mya-Astarte* association. Samples from Facies 3, 5, 6, and 7 represent a most diverse *Hiatella-Mya-Astarte-Serripes* association relative to Facies 1. The *Portlandia* association is the only association that preserved in Facies 4, composed by *Portlandia arctica* only or associated with *Hiatella arctica*.

6.7.2 Faunal Succession

According to the mollusc associations preserved in the glaciomarine sediments (Table 6.5), changes in faunal composition can be divided into four stages beginning with the Last Glacial Maximum in the early Holocene ca. 10 ka BP in the High Arctic (Table 6.6). This succession of molluscan faunas compares favourably with molluscan faunas recorded in previous studies (Spjeldnaes, 1978; Thomsen and Vorren, 1986; Syvitski *et al.*, 1989; Lemmen *et al.*, 1994; Dyke *et al.*, 1996a; Simonarson *et al.*, 1998; Gordillo and Aitken, 2001).

The period beginning in the late Pleistocene before deglaciation was characterized by a benthic fauna dominated by the infaunal suspension bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* to the benthic fauna, which was preserved and overridden by the glaciers that deposited Facies 1. During the early phase of deglaciation, *Portlandia arctica* appeared as the pioneer species that dominated in ice-proximal marine environments preserved in Facies 4. Subsequent faunal diversification throughout the early and middle postglacial period is recorded, first, by the additions of infaunal suspension/deposit bivalves, such as *Hiatella arctica*, *Mya*

truncata, and *Astarte borealis* recorded in Facies 2 to the benthic fauna and, later, a more diverse fauna results from the addition of *Macoma calcarea*, *Serripes groenlandicus*, and *Clinocardium ciliatum* recorded from Facies 3. The development of modern marine environments is characterized by the addition of *Musculus* sp., *Thracia* sp., *Nuculana pernula*, *Nucula belloti*, *Buccinum* sp. and *Margarites* sp. from Facies 5, 6, and 7, as part of diverse mollusc associations during the late post-glacial period.

6.7.3 Paleo-marine Environments

During the first stage of deglaciation in the study area, the *Portlandia* association is common in rhythmically bedded / laminated ice-proximal glaciomarine sediments (Facies 4). The extensive sea ice cover and iceberg production before 10 ka BP would have chilled surface waters and delayed seasonal warming (Stewart and England, 1983; Rodrigues, 1988; Bradley, 1990; Bell, 1996; Dyke *et al.*, 1996b; Bednarski, 1998). Only the most robust bivalves, *Portlandia arctica* and *Hiatella arctica* survived through the Last Glacial Maximum and the initial rapid retreat of glacier margins by ca. 9.5 ka BP, in that they were able to tolerate rapidly changing environmental conditions associated with rapid sedimentation, cold water of reduced salinity, and limited marine primary production, and environmental change.

The *Hiatella-Mya-Astarte* association was observed in the early postglacial period. The addition of *Mya truncata* and *Astarte* spp. to benthic fauna is associated with this period of the reduced summer sea ice cover, the rapid retreat of glaciers, the reduction of clastic sedimentation in nearshore environments, and an increased surface water temperatures and marine primary production (Bradley, 1990).

Table 6.6 Comparison of macrofaunal succession in arctic marine mollusc assemblages.

Geographical region	Macrofaunal succession			Source
	Survivor or pioneer groups		Variated group	
Axel Heiberg Island	*Portlandia arctica*	*Hiatella arctica* *Mya truncata* *Astarte* sp.	*Serripes groenlandicus* *Macoma calcarea* *Musculus* sp. *Thracia* sp. *Nuculana pernula* *Nucula belloti* *Buccinum* sp. *Margarites* sp.	This study
Prince of Wales Island	*Hiatella arctica* (11ka BP); *Mya truncata* (9.8 ka BP)	*Macoma calcarea* (9.6 ka BP) *Portlandia arctica* (9.6 ka BP)	*Astarte borealis* (8.51 ka BP) *Clinorcardium ciliatum*; *Serripes groenlandicus* (8.5 ka BP)	Gordillo and Aitken, 2001
Baffin Island	*Portlandia arctica*	Mature *Portlandia* association: *Portlandia arctica* *Hiatella arctica* *Mya truncata* *Macoma calcarea*	Onuphid Association: *Chlamys islandica* *Astarte* spp. *Musculus* sp.	Syvitski *et al*., 1989
Expedition Fiord	-	*Hiatella-Mya* assemblage (8.1-8.4 ka BP) *Hiatella arctica* *Mya truncata*	*Astarte-Mya* assemblages (7.9 ka BP) *Astarte borealis* *Mya truncata*	Lemmen *et al*., 1994
Northern Norway		*Bathyarca glacialis* Assemblages (13-10 ka BP) (Arctic species, i.e., *Bathyarca glacialis, Yoldiella intermedia, Yoldiella frigida,* etc.)	*Kelliela miliaris* Assemblages (7.8 ka BP) (Boreal-Lusitanian, Boreal-Arctic species, i.e., *Bathyarca glacialis, Yoldiella intermedia, Yoldiella fraterna, Nuculana tenis*, etc.)	Thomsen and Vorren, 1986
Oslo Fiord (Denmark)	*Portlandia-Macoma* association	*Chlamys-Lepeta* association		Spjeldnæs, 1978
North Greenland	*Portlandia arctica-Tridonta montagui* Assemblage	*Hiatella arctica-Cyrtodaria kurriana-Portlandia arctica* Assemblage	*Macoma balthica-Tridonta borealis- Cyrtodaria kurriana* Assemblage	Simonarson *et al*., 1998
Western Champlain Sea	*Portlandia arctica* *Macoma balthica*	*Hiatella arctica* *Mya truncata*	*Hiatella arctica* *Macoma balthica* *Mya truncata* *Mya arenaria* *Mytilus edulis*	Rodrigues, 1988

The early to mid- Holocene period was characterized by warm temperatures and the generation of substantial amounts of summer meltwater from alpine glaciers (Bradley, 1990; Koerner and Fisher, 1990). Dyke *et al*. (1997) observed that a large bowhead population extended in the summer to retreating glacier margins and ultimately from the Beaufort Sea to Baffin Bay during this interval of time. This period also coincides with the initial incursion of driftwood into the archipelago (Stewart and England, 1983; Dyke *et al.*, 1997).

A more diverse *Hiatella-Mya-Astarte-Serripes* association developed during the mid-Holocene with the addition of arctic-boreal species such as *Macoma calcarea*, *Clinorcardium ciliatum*, *Serripes groenlandicus*, *Musculus spp.*, and *Nuculana pernula*. This more diverse fauna appeared in fine-grained shallow marine sediments (Facies 3). This situation reflects the continued amelioration of the regional climate until 8 ka BP which allowed subarctic species to penetrate and survive in the High Arctic during this period (Dyke *et al.*, 1996a; Gordillo and Aitken, 2001).

Regional retreat of glacier margins became slower within study area between 8 to 5 ka BP. By 8 ka BP the flow of surface water from the Arctic Ocean through the archipelago was established, replacing the previous meltwater-dominated outflow (Dyke *et al.*, 1996a). Consequently, sea ice conditions in the inter-island channels became severe and excluded the entry of bowhead whales between 8 ka an 6 ka BP (Dyke *et al.*, 1997). Meanwhile, the increasing abundance of driftwood probably recorded a westward shift of Transpolar Drift which carried driftwood across the Arctic

Ocean to the beaches in the high arctic from the north of the Canadian Arctic Archipelago.

With the development of modern marine environments during the late postglacial period, "the influx of meltwater and clastic sediments [was] reduced considerably; organic materials supplied to the benthos are derived largely from marine sources" (Gordillo and Aitken, 2001: p. 70). Nearshore benthic faunas are characterized by the *Hiatella-Mya-Astarte-Serripes* association preserved in shallow marine or estuarine sediments (Facies 5, 6, and 7) during this period. Summer sea ice conditions must have ameliorated by 5 ka BP. Dyke *et al*. (1996b) observed that bowhead whales reoccupied the central channels of the Arctic Islands between 5 to 3 ka BP. Boreal species (i.e. *Chlamys islandica*) reached their northernmost recorded position on east-central Ellesmere Island during this interval of time (Dyke *et al.*, 1996a). The species composition of the fossil associations is similar to modern marine benthic communities with diverse arctic and subarctic molluscs.

6.8 Summary

1. Ecology and Macrofaunal Association

The molluscs recorded in the fossil assemblages examined in this study typically inhabit shallow waters and are adapted to substrates ranging from rocky bottoms to unconsolidated sediments. Suspension-feeding bivalves were preferentially preserved in the fossil assemblages associated with the post-glacial sediments. These patterns of macrofossil preservation corroborate observations of macrofossil preservation elsewhere in high arctic regions (Aitken, 1990; Lemmen *et al.*, 1994; Aitken and Bell, 1998; Simonarson *et al.*, 1998; Gordillo and Aitken, 2001).

The composition of the six groups recognized in the clustering analysis is comparable to the composition of modern communities inhabiting nearshore environments in fjords and on the continental shelf of the eastern Canadian Arctic (Dale *et al.*, 1989; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993; Dyke *et al.*, 1996a; Gordillo and Aitken, 2001). The six macrofaunal associations do not distinctly correspond to the facies identified from the associated sediments in this study, except that *Portlandia* association occurs in facies correspond to ice-proximal environments.

2. Preservation Pattern

Serripes exhibits the greatest degree of fragmentation, followed by *Hiatella*, *Mya*, and *Astarte* with the lowest degree of fragmentation, which indicate different preservation potential of the four species. Shells with high (or low) degree of fragmentation for single species (i.e. *Hiatella*) also correspond to the associated sediments facies from which the shells are recovered. The loss of shell luster among all samples of *Hiatella*, *Mya*, *Astarte*, *Serripes* and *Portlandia* suggests that this taphonomic feature is not indicative of the energy of depositional environment but probably corresponds to the long-term taphonomic processes associated with the enclosing sediments. The general absence of strongly bioeroded or encrusted shells among samples of *Hiatella*, *Mya*, *Astarte* and *Serripes* and the absence of bioeroded or encrusted *Portlandia* shells suggests rapid burial of the shells with only limited exposure on the sediment surface, or the absence of grazing, boring or encrusting taxa in the environment (Parsons and Brett, 1991). This result is consistent with infaunal habit of most of the taxa represented in the shell assemblages.

Shell disarticulation and fragmentation can result from sea ice scouring of the seafloor and the development of permafrost in raised marine sediments. Most of our samples are not substantially transported nor significantly reworked. The degree of shell disarticulation for the four most common taxa is generally low which likely reflects high sedimentation rates and rapid burial in nearshore environments, especially those from glaciomarine silts and estuarine deposits. Shells with high degree of disarticulation from five samples associated with diamicton and raised beach ridges are expected to experience a considerable degree of reworking by glaciers, waves, and sea ice. A single sample associated with a high energy estuarine environment characterized by the deposition of pebbly sand and gravel with algal debris, bears evidence of disturbance by a combination of fluvial and marine processes. Left and right valves of *Mya truncata* in this study are more susceptible to wave effects than those of other species due to their distinct valve shape among the species.

The great majority of shells in these samples are adult shells. More juvenile shells of *Astarte borealis* are represented in the mollusc assemblages than those of *Hiatella arctica* and *Mya truncata*. The relatively narrow ranges of *Hiatella* and *Mya* may be related to the species relatively poor resistance to shell breakage through time. The presence of diverse species characterized by normally small shells (i.e. *Astarte montagui*, *Portlandia arctica*, *Nuculana pernula*, *Lyonsia arenosa*, *Thyasira* sp., *Oenopota* sp., and *Cylichna* sp) and their relatively poor resistance to breakage, provides evidence of limited transportation or exposure on the sea floor for any length of time. *Astarte borealis* exhibits bimodal size-frequency distributions in a few samples, which may suggest that a catastrophic event might influence the preservation of the size

structure of a living population with no evidence of physical transportation, or a large input pulse with a size-distribution different from that already present in the death assemblage might insert a secondary mode into the size-frequency distribution (Cummins *et al.*, 1986).

Four taphofacies are distinguished in this study on the basis of cluster analysis of four taphonomic variables (fragmentation, corrasion, bioerosion, and encrustation). Shells exhibiting poor preservation (*Taphofacies I*) are recovered from Facies 1 and 2 reflecting high energy environments, Facies 3 reflecting lower energy offshore muds with the potential for prolonged exposure of exhumed shells on the seafloor as these sediments emerge above sea level, and Facies 4 where crushing of small shells is related to permafrost aggradation following emergence of these sediments above sea level. Shells exhibiting fair preservation (*Taphofacies II*) are recovered from Facies 7 associated with rapid sedimentation in nearshore environments, where shells can probably be crushed after burial by postmortem effects such as permafrost aggradation. Shells exhibiting fair to good preservation (*Taphofacies III*) are recovered from shallow marine or estuarine (Facies 5, 6 and 7) depositional environments that correspond to the high rates of sedimentation in these nearshore environments. Shells identified as *Taphofacies IV* are recovered from Facies 4 (proglacial) where shells recovered from these sediments can be considerably fragmented and highly abraded/corroded by exhumation on the seafloor or permafrost aggradation after emergence of the sediments, though high rates of sedimentation are expected.

3. Faunal Comparison with Modern Communities

Each species presently inhabits marine waters within the Canadian Arctic Archipelago, except for *Mya pseudoarenaria*. This species presently inhabiting shallow water (2-30 m depth) in the low arctic (i.e. in eastern Hudson Bay), is absent from modern benthic mollusc faunas in the High Arctic and was more widespread in early postglacial time and. Based the argument by Dyke *et al.* (1996a) that it did not survive in the Arctic Ocean through the last glacial maximum, we suspect the fossil assemblages containing *Mya pseudoarenaria* are early to middle Holocene in age.

The large relative abundance of *Mya truncata* in the fossil assemblages is distinguished from its low relative abundance in the modern faunas. This probably reflects the method of sampling modern benthos in that benthic trawls and grab samplers underestimate the presence of deeply buried (>5 cm depth) infaunal organisms, such as *Mya truncata* (Thomsen and Vorren, 1986; Gordillo and Aitken, 2000). The relatively low abundance and/or absence of the taxa, *Nucula*, *Portlandia*, *Thyasira*, *Thracia*, *Bathyarca glacialis* and *Axinopsida orbiculata*, in the macrofossil assemblages may be attributed to a variety of biostratinomic processes, their small, thin shells that are more susceptible to postmortem solution and fragmentation than larger and/or thicker shells, and their relative rarity in the modern fauna. The gastropod taxa *Colus*, *Buccinum*, and *Margarites* are widely distributed but always occur in low abundance in the Canadian Arctic and Greenland, possibly due to their low abundance in modern benthic mollusc communities and their lower preservation potential relative to infaunal bivalves.

The relative abundance of trophic groups in this study (suspension-feeders > deposit feeders > carnivores > browsers), is consistent with the result of several studies of fossil

mollusc assemblages due to "different initial abundances between trophic groups, and differences in the preservation related to mobility and the nature of mineralized body parts" (Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000). Species compositional fidelity can be significantly affected by skeletal modification initialized by sea-ice scouring in shallow Arctic marine environments (Bibeau *et al.*, 2005).

4. Faunal Succession

Changes in faunal composition can be divided into four stages beginning with the Last Glacial Maximum in the early Holocene ca. 10 ka BP in the High Arctic. A benthic fauna dominated by the infaunal suspension bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* during the period beginning in the late Pleistocene before deglaciation, *Portlandia arctica* as the pioneer species that dominated in ice-proximal marine environments during the early phase of deglaciation, a first faunal diversification by the additions of infaunal suspension/deposit bivalves, such as *Hiatella arctica*, *Mya truncata*, and *Astarte borealis* throughout the early and middle postglacial period, a later more diverse fauna with the addition of *Macoma calcarea*, *Serripes groenlandicus*, and *Clinocardium ciliatum*, and the development of modern marine environments by the addition of *Musculus* sp., *Thracia* sp., *Nuculana pernula*, *Nucula belloti*, *Buccinum* sp. and *Margarites* sp. This succession of molluscan faunas compares favourably with records in previous studies (Thomsen and Vorren, 1986; Syvitski *et al.*, 1989; Lemmen *et al.*, 1994; Dyke *et al.*, 1996a; Gordillo and Aitken, 2001).

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

A total of 5065 specimens (5018 valves of bivalve and 47 gastropod shells) have been identified and classified into 27 species. The bivalves *Hiatella arctica*, *Mya truncata*, *Astarte borealis*, and *Serripes groenlandicus* are the most common species represented in 55 samples from three localities (Gibbs Fiord, Mokka Fiord, and Eureka Sound). Each species presently exists within the Canadian Arctic Archipelago, except for *Mya pseudoarenaria*. Our samples record the dominance of infaunal suspension-feeders (i.e., *Astarte*, *Clinocardium*, *Hiatella*, *Mya*, *Macoma*, *Serripes*, and *Thracia*) that are most abundant on soft substrates typically occurring in from the intertidal zone to depths of ~50 meters or more in nearshore environments associated with polar or fjord water masses and influenced by sea ice and iceberg scouring. The normal minimum salinity of these species varies from euryhaline to 20~30‰ with a common temperature range of -2°C to ~10°C. Most of the species have Arctic-Boreal and circumpolar distributions with geological ranges from Miocene or Pleistocene to Recent. Most of the bivalves are mobile forms burrowing into the substrata. Most of the gastropods live as vagrant predators except only for *Trichotropis*, which is a suspension-feeder. The dominance of bivalves with respect to gastropods reflects a time-averaged record of the fossil assemblages inhabiting the high latitude nearshore environments.

The trophic composition of the paleocommunities is as follows: suspension-feeders (96.78%; n = 4902) > deposit feeders (2.41%; n = 122) > carnivores (0.75%; n = 38) > browsers (0.06%; n = 3), due to "different initial abundances" between trophic groups, and "differences in the preservation related to mobility and the nature of mineralized body parts" (Gordillo and Aitken, 2000: 305). This relative abundance of trophic groups is consistent with the results of several paleoecology studies (i.e. Aitken, 1990; Palmqvist, 1991; Gordillo and Aitken, 2000). Suspension feeders were evidently preferentially preserved in the sediments of high arctic regions (see Aitken, 1990; Gordillo and Aitken, 2001), reflecting the high preservation potential of infaunal, thick-shelled taxa.

Six unique associations are recognized from cluster analysis as the *Portlandia* association, the *Astarte* association, the *Mya* association, the *Hiatella-Mya* association, the *Hiatella-Mya-Astarte-Serripes* association, and the *Hiatella-Mya-Astarte* association, according to species composition. The composition of these associations is comparable to the composition of modern communities inhabiting fiord and nearshore continental shelf environments (Dale *et al.*, 1989; Syvitski *et al.*, 1989; Aitken and Fouriner, 1993; Dyke *et al.*, 1996a; Gordillo and Aitken, 2001). Deposit feeders (i.e. *Portlandia arctica*, *Macoma* spp. and *Nuculana*), suspension-feeders (i.e. *Hiatella, Mya, Astarte,* and *Serripes*), and rare taxa (i.e. *Buccinum*, *Musculus*, *Pandora*, and *Nuculana pernula*) as three groups of taxa recognized from MDS R-mode analysis. The six macrofaunal associations do not distinctly correspond to the facies identified from the associated sediments in this study, except that the *Portlandia* association occurs in facies correspond to ice-proximal environments.

Four common species exhibit different preservation potential based the degree of fragmentation and disarticulation (*Serripes* < *Mya* < *Hiatella* < *Astarte*). Shells with high (or low) degree of fragmentation for single species (i.e. *Hiatella*) also correspond to different environmental energy conditions of the associated sediments facies from which the shells are recovered (Facies 1 ≈ Facies 2 > Facies 3 ≈ Facies 4 > Facies 5 > Facies 6 ≈ Facies 7). Shell luster in this study is not indicative of the energy of depositional environment but probably corresponds to the long-term taphonomic processes associated with the enclosing sediments. The general absence of strongly bioeroded or encrusted shells among samples suggests rapid burial of the shells with only limited exposure on the sediment surface, or the absence of grazing, boring or encrusting taxa in the environment (Parsons and Brett, 1991). This result is consistent with the infaunal habit of most of the taxa represented in the shell assemblages.

Most of the samples are not substantially transported nor significantly reworked. Shell disarticulation and fragmentation can result from sea ice scouring of the seafloor and the development of permafrost in raised marine sediments. The degree of shell disarticulation for the four most common taxa is generally low which likely reflects high sedimentation rates and rapid burial in nearshore environments, especially those from glaciomarine silts and estuarine deposits. Shells with high degree of disarticulation from five samples associated with diamicton and raised beach ridges are expected to experience a considerable degree of reworking by glaciers, waves, and sea ice. A single sample associated with a high energy estuarine environment characterized by the deposition of pebbly sand and gravel with algal debris, bears evidence of disturbance by a combination of fluvial and marine processes.

Seven guilds are identified for Bivalvia and Gastropoda: infaunal suspension-feeder, infaunal deposit-feeder, semi-infaunal suspension-feeder, epifaunal suspension-feeder, epifaunal predator, infaunal predator, and grazer. Infaunal suspension-feeders (> 60%) and semi-infaunal suspension-feeders (>30%) together dominate in the paleocommunity with a contribution of more than 96% of all the individuals in the paleocommunity. Infaunal deposit-feeders contribute only 2.34% to the proportion of abundance. Epifaunal suspension-feeders and infaunal predators are poorly preserved while most epifaunal predators and grazers are lost.

Four taphofacies are recognized by cluster analysis on the basis of four taphonomic variables (fragmentation, corrasion, bioerosion, and encrustation) characterized by poor preservation, fair preservation, fair-good preservation, and fair preservation with poor corrasion respectively. Faunal succession and paleo-marine environments during the deglaciation in early Holocene can be reconstructed from the seven sedimentation facies (glacial, beaches, shallow marine, proglacial, shallow marine or estuarine - pebbly sand and gravel with algal debris, shallow marine or estuarine - pebbly silt with algal debris, shallow marine or estuarine - interbedded silt and sand).

During the first stage of deglaciation in the study area, the extensive sea ice cover and iceberg production before 10 ka BP would have chilled surface waters and delayed seasonal warming (Stewart and England, 1983; Bradley, 1990; Bell, 1996; Dyke *et al.*, 1996b; Bednarski, 1998). Only the most robust bivalves, *Portlandia arctica* and *Hiatella arctica* survived through the Last Glacial Maximum and the initial rapid retreat of glacier margins by ca. 9.5 ka BP, in that they were able to tolerate rapidly changing

environmental conditions associated with rapid sedimentation, cold water of reduced salinity, and limited marine primary production, and environmental change. Preceding the Last Glacial Maximum, the *Hiatella-Mya-Astarte* association was observed in the early postglacial period associated with the reduced summer sea ice cover, the rapid retreat of glaciers, the reduction of clastic sedimentation in nearshore environments, warmer surface water temperatures, and increased marine primary production (Bradley, 1990). This period also coincides with a large bowhead population that extended in the summer to retreating glacier margins observed by Dyke *at el*. (1996b) and an initial incursion of driftwood into the archipelago observed by Stewart and England (1983) and Dyke *et al.* (1997) during this interval of time. A more diverse *Hiatella-Mya-Astarte-Serripes* association developed during the mid-Holocene with the addition of arctic-boreal species such as *Macoma calcarea*, *Clinorcardium ciliatum*, *Serripes groenlandicus*, *Musculus spp.*, and *Nuculana pernula*, which reflecting the continued amelioration of the regional climate until 8 ka BP (Dyke *et al.*, 1996a; Gordillo and Aitken, 2001). Regional retreat of glacier margins became slower within study area between 8 to 5 ka BP. The flow of surface water from the Arctic Ocean through the archipelago was established and sea ice conditions in the inter-island channels became severe and excluded the entry of bowhead whales between 8 ka an 6 ka BP (Dyke *et al.*, 1996a; Dyke *et al.*, 1997). With the development of modern marine environments during the late postglacial period, nearshore benthic faunas are characterized by the *Hiatella-Mya-Astarte-Serripes* association. Summer sea ice conditions must have ameliorated by 5 ka BP. The species composition of the fossil associations is similar to modern marine benthic communities with diverse arctic and subarctic molluscs.

7.2 Recommendation for Future Research

The utility of MDS for classification requires further investigation related to two-dimensional and three-dimensional solutions. MDS allows an operator to investigate the dimension values of the samples and compare the distance between each sample in the derived two-dimensional space (coordinate), however, this task is difficult to do in three or more dimensional space. In this study, feeding mode and relative abundance of taxa are highlighted respectively by dimension 1 and 2 in MDS derived coordinates. Optimal solutions differ from one study to another. Advanced statistical methods should be able to prevent compromising the number of dimensions in order to improve simulation and interpretation of dimensions.

Future research on modern benthic communities is expected to shed light on the influence of sea ice on the community structure of the modern marine benthos and the preservation of mollusk shells in nearshore sediments. The variance of sea ice cover will change the salinity and temperature of the habitat, but also affect the taphonomic features of the shells during the processes of diagenesis and biostratinomy. Severe shell fragmentation and surface alteration and extensive erosion of the seafloor by sea ice have been observed by Bibeau *et al.* (2005) from Resolute Bay, Canada. Comparison of the modern and fossil benthic molluscan communities affected by sea ice scouring needs to be studied, in order to help understand the effects of sea ice on macrofossil assemblages, which will make it more evident and easier for the paleoenvironmental reconstruction.

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Appendix I: List of Samples And Taphonomic Data

Table 1. Taxonomic composition of raised marine sediments of Eureka Sound and glacial tills of Mokka Fiord

	ES-Sh2-0707	ES-Sh3-0807	ES-Sh4-0807	ES-Sh5a-0807	ES-Sh5b-0807	ES-Sh6-0807	ES-Sh8-0802	ES-Sh9-0907	ES-Sh10-0907	ES-Sh17-0907	ES-Sh18-0907	ES-Sh19-0907	ES-Sh20-0907	ES-Sh21-0907	ES-Sh22-0907	ES-Sh23-0907	ES-Sh24-0907	ES-Sh25-1007	ES-Sh27-1207	ES-Sh28-1207	ES-Sh29-1207	ES-Sh30-1207	ES-Sh31-1207	ES-Sh32-1207	ES-Sh33-1207	MF-12-S-2998	MF-13-S-2998	MF-14-S-3098	MF-16-S-0198	MF-18-S-0298	MF-19-S-0298	MF-20-S-0398	MF-21-S-0498	MF-23-S-0598	MF-26A/S-0898	MF-26C/S-0898	MF-26D/S-0898	MF-26E/S-0898	MF-27-S-0998	MF-28-S-0998	MF-29-S-0998	ES-01-S-9402	ES-03-S-9404	ES-04A-S-9404	ES-04D-S-9404	ES-04E-S-9404	ES-04F-S-9404	ES-05-S-9405	ES-08-S-9405	ES-09-S-9406	ES-10-S-9407	ES-11-S-9408	ES-15-S-9418	ES-17-S-9421	ES-18-S-9421
Hiatella arctica		x	x	x	x			x	x	x									x		x	x	x		x	x	x	x	x		x		x		x			x	x	x	x	x	x	x	x	x	x			x	x	x	x
Mya truncata		x	x	x	x	x		x		x		x	x	x	x				x		x	x	x		x	x	x	x	x		x	x	x	x				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Mya pseudoarenaria										x									x																																				
Serripes			x	x	x			x		x	x		x	x	x				x	x		x	x				x				x	x		x				x	x	x	x	x	x	x	x	x			x	x	x	x
Astarte borealis	x	x	x	x	x			x	x	x				x	x	x	x		x	x	x	x	x	x	x	x	x			x	x	x		x				x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x
A. montagui					x					x					x				x		x	x	x	x						x									x	x	x	x		x	x	x	x	x					x	x
Macoma calcarea		x		x	x																			x															x				x		x		x						x
M. loveni											x								x																											x									
M. moesta																			x																																			
Clinocardium																			x				x																															
Portlandia				x			x											x												x						x	x	x																x
Musculus niger									x						x				x				x																	x		x				x	x	x						
M. corrugatus																				x																																		
M. discor																																																						
Nucula belloti																																																					
Nuculana pernula																			x																																		
Thracia myopsis									x										x																																		
Pandora glacialis																			x	x																																	
Thyasira sp.																																																				
Lyonsia arenosa																																																				
Buccinum finmarkianum																			x																																		
Buccinum totteni																			x	x																																	
Margarites olivacens																			x																																		
Cylichna sp.																																																				
Oenopota c.f. cinerea																																																				
Trichotropis borealis																																																				
Colus c.f. togatus																																																				

Data pooled at sample level, presence/absence of taxa or species expressed in binary data ("x" = present, otherwise absent).
ES: Eureka Sound: MF: Mokka Fiord.

Table 2 Taphonomic data of 11 taxa/species from Eureka Sound and Mokka Fiord used in taphograms pooled at sample level

A. Fragmentation

	Nuculana pernula				*Portlandia arctica*				*Musculus sp.*				*Astarte sp.*				*Serripes*				*Macoma sp.*				*Mya truncata*				*Hiatella arctica*				*Thracia myopsis*				*Pandora glacialis*				*Buccinum sp.*			
Taphonomic grade	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M
ES-Sh2-0707													20	60	20	1.0																												
ES-Sh3-0807													0	0	100	2.0					0	100	0	1.0	0	0	100	2.0	5	11	84	1.8												
ES-Sh4-0807													0	67	33	1.3	0	0	100	2.0					0	3	97	2.0	0	8	92	1.9												
ES-Sh5a-0807					100	0	0	0.0					50	50	0	0.5	0	0	100	2.0	9	82	9	1.0	50	39	11	0.6	0	100	0	1.0												
ES-Sh5b-0807													45	42	13	0.7	0	0	100	2.0	0	92	8	1.1	0	50	50	1.5	0	0	100	2.0												
ES-Sh6-0807																									0	100	0	1.0																
ES-Sh8-0802					57	14	29	0.7																																				
ES-Sh9-0907													67	33	0	0.3	0	40	60	1.6					0	0	100	2.0	50	38	13	0.6												
ES-Sh10-0907									0	0	100	2.0	100	0	0	0.0													50	50	0	0.5	100	0	0	0.0								
ES-Sh17-0907													37	53	11	0.7	0	13	88	1.9					29	14	57	1.3	40	20	40	1.0												
ES-Sh18-0907																	25	25	50	1.3	50	50	0	0.5																				
ES-Sh19-0907																									50	50	0	0.5																
ES-Sh20-0907																	100	0	0	0.0					0	0	100	2.0																
ES-Sh21-0907													71	29	0	0.3	0	33	67	1.7					0	0	100	2.0																
ES-Sh22-0907									0	100	0	1.0	80	20	0	0.2	0	20	80	1.8					50	50	0	0.5																
ES-Sh23-0907													100	0	0	0.0																												
ES-Sh24-0907													0	100	0	1.0																												
ES-Sh25-1007																																												
ES-Sh27-1207	100	0	0	0.0					100	0	0	0.0	89	9	1	0.1	33	45	21	0.9	33	67	0	0.7	74	22	5	0.3	64	28	8	0.4	0	0	100	2.0	0	100	0	1.0	67	33	0	0.3
ES-Sh28-1207									0	50	50	1.5	100	0	0	0.0	0	0	100	2.0																	0	100	0	1.0	0	50	50	1.5
ES-Sh29-1207													60	33	7	0.5									89	6	6	0.2	46	15	38	0.9												
ES-Sh30-1207													80	20	0	0.2	40	40	20	0.8					82	18	0	0.2	75	25	0	0.3												
ES-Sh31-1207									100	0	0	0.0	45	55	0	0.5	0	0	100	2.0					90	0	10	0.2	76	24	0	0.2												
ES-Sh32-1207													46	54	0	0.5					0	100	0	1.0																				
ES-Sh33-1207													100	0	0	0.0									0	67	33	1.3	0	67	33	1.3												
MF-12-S-2998													26	68	6	0.8									0	0	100	2.0	0	0	100	2.0												
MF-13-S-2998																									0	0	100	2.0	11	22	67	1.6												
MF-14-S-3098																									0	7	93	1.9																
MF-16-S-0198																									0	0	100	2.0	0	0	100	2.0												
MF-18-S-0298					8	92	0	0.9					50	49	1	0.5													0	0	100	2.0												
MF-19-S-0298													25	75	0	0.8	0	0	100	2.0					0	50	50	1.5																
MF-20-S-0398																	0	0	100	2.0					0	0	100	2.0	0	0	100	2.0												
MF-21-S-0498																									0	0	100	2.0																
MF-23-S-0598													12	84	4	0.9	0	0	100	2.0					0	0	100	2.0	0	0	100	2.0												
MF-26A/S-0898																																												
MF-26C/S-0898																																												
MF-26D/S-0898					0	100	0	1.0																																				
MF-26E/S-0898					0	100	0	1.0																																				
MF-27-S-0998									0	100	0	1.0	33	65	1	0.7	2	35	63	1.6	0	100	0	1.0	0	29	71	1.7	67	29	4	0.4												
MF-28-S-0998													22	72	7	0.8	0	21	79	1.8					13	38	50	1.4	80	20	0	0.2												
MF-29-S-0998	0	0	100	2.0					0	100	0	1.0	5	92	3	1.0	14	29	57	1.4					55	37	8	0.5	29	56	15	0.9												
ES-01-S-9402													13	88	0	0.9	0	0	100	2.0					0	0	100	2.0	14	53	32	1.2												
ES-03-S-9404																	0	0	100	2.0					0.0	0.6	99.4	2.0	0	43	57	1.6												
ES-04A-S-9404													71	29	0	0.3	50	29	21	0.7	0	100	0	1.0	70	30	0	0.3	80	20	0	0.2												
ES-04D-S-9404									0	100	0	1.0	65	35	0	0.4	44	56	0	0.6					43	43	14	0.7	88	13	0	0.1									0	50	50	1.5
ES-04E-S-9404	19	0	81	1.6					0	0	100	2.0	73	25	2	0.3	9	9	82	1.7	0	0	100	2.0	100	0	0	0.0	57	29	14	0.6	100	0	0	0.0								
ES-04F-S-9404									0	33	67	1.7	13	86	1	0.9	0	37	63	1.6					9	45	45	1.4	14	86	0	0.9	0	67	33	1.3								
ES-05-S-9405													0	25	75	1.8	0	0	100	2.0					0	0	100	2.0	17	57	26	1.1												
ES-08-S-9405													57	43	0	0.4					0	100	0	1.0	7	21	71	1.6																
ES-09-S-9406													0	40	60	1.6	0	0	100	2.0					0	0	100	2.0	0	3	97	2.0												
ES-10-S-9407																									0	0	100	2.0	7	60	33	1.3												
ES-11-S-9408																									0	0	100	2.0																
ES-15-S-9418																	0	0	100	2.0					0	0	100	2.0	0	0	100	2.0												
ES-17-S-9421													3	8	89	1.9	0	0	100	2.0					0	0	100	2.0	0	25	75	1.8												
ES-18-S-9421					80	20	0	0.2					30	70	0	0.7	0	0	100	2.0					8	38	54	1.5	13	80	7	0.9												

"M" = mean

Table 2 B. Corrasion

Taphonomic grade	*Nuculana pernula*					*Portlandia arctica*					*Musculus sp.*					*Astarte sp.*					*Serripes*					*Macoma sp.*					*Mya truncata*					*Hiatella arctica*					*Thracia myopsis*					*Pandora glacialis*					*Buccinum sp.*				
	"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M		"0"	"1"	"2"	M	
ES-Sh2-0707																0	100	0	1.0																																			
ES-Sh3-0807																0	100	0	1.0						0	100	0	1.0		0	0	100	2.0		0	79	21	1.2																
ES-Sh4-0807																0	67	33	1.3	0	0	100	2.0							0	0	100	2.0		0	0	100	2.0																
ES-Sh5a-0807						0	100	0	1.0							0	88	13	1.1	0	100	0	1.0		0	45	55	1.5		0	61	39	1.4		0	100	0	1.0																
ES-Sh5b-0807																0	85	15	1.1	0	0	100	2.0		0	58	42	1.4		0	33	67	1.7		0	100	0	1.0																
ES-Sh6-0807																														0	0	100	2.0																				
ES-Sh8-0802						0	0	100	2.0																																															
ES-Sh9-0907																0	83	17	1.2	0	0	100	2.0							0	100	0	1.0		0	100	0	1.0																
ES-Sh10-0907											0	100	0	1.0		0	100	0	1.0																100	0	0	0.0	0	100	0	1.0												
ES-Sh17-0907																0	68	32	1.3	0	25	75	1.8							0	0	100	2.0		0	80	20	1.2																
ES-Sh18-0907																				0	100	0	1.0		0	100	0	1.0																												
ES-Sh19-0907																														0	100	0	1.0																				
ES-Sh20-0907																				0	100	0	1.0							0	100	0	1.0																				
ES-Sh21-0907																0	57	43	1.4	0	11	89	1.9							0	0	100	2.0																				
ES-Sh22-0907											0	100	0	1.0		0	80	20	1.2	0	40	60	1.6							0	100	0	1.0																				
ES-Sh23-0907																0	100	0	1.0																																		
ES-Sh24-0907																0	100	0	1.0																																		
ES-Sh25-1007																																																				
ES-Sh27-1207	0	0	100	2.0							0	100	0	1.0		5	88	6	1.0	0	77	23	1.2		0	100	0	1.0		0	82	18	1.2		0	84	16	1.2		0	100	0	1.0		0	0	100	2.0		1	2	0	0.7
ES-Sh28-1207											0	0	100	2.0		0	100	0	1.0	0	25	75	1.8																										0	0	100	2.0		0	2	0	1.0
ES-Sh29-1207																0	73	27	1.3											0	89	11	1.1		0	100	0	1.0																
ES-Sh30-1207																0	88	12	1.1	0	60	40	1.4							0	91	9	1.1		0	100	0	1.0																
ES-Sh31-1207											0	100	0	1.0		0	91	9	1.1	0	100	0	1.0							0	60	40	1.4		0	100	0	1.0																
ES-Sh32-1207																0	77	23	1.2						0	100	0	1.0																												
ES-Sh33-1207																0	0	100	2.0											0	33	67	1.7		0	100	0	1.0																
MF-12-S-2998																0	80	20	1.2											0	100	0	1.0		0	33	67	1.7																
MF-13-S-2998																														0	6	94	1.9		0	78	22	1.2																
MF-14-S-3098																														0	9	91	1.9																				
MF-16-S-0198																														0	0	100	2.0		0	33	67	1.7																
MF-18-S-0298						0	84	16	1.2							1	95	3	1.0																0	100	0	1.0																
MF-19-S-0298																0	100	0	1.0	0	20	80	1.8							0	75	25	1.3																				
MF-20-S-0398																				0	0	100	2.0							0	0	100	2.0		0	60	40	1.4																
MF-21-S-0498																														0	0	100	2.0																				
MF-23-S-0598																0	88	12	1.1	0	100	0	1.0							0	50	50	1.5		0	100	0	1.0																
MF-26A/S-0898																																																						
MF-26C/S-0898																																																					
MF-26D/S-0898						0	100	0	1.0																																													
MF-26E/S-0898						0	100	0	1.0																																													
MF-27-S-0998											0	100	0	1.0		0	78	22	1.2	0	42	58	1.6		0	0	100	2.0		0	24	76	1.8		0	62	38	1.4																
MF-28-S-0998																0	89	11	1.1	0	64	36	1.4							0	69	31	1.3		0	60	40	1.4																
MF-29-S-0998	0	100	0	1.0							0	100	0	1.0		0	97	3	1.0	0	100	0	1.0							0	95	5	1.1		0	97	3	1.0																
ES-01-S-9402																0	50	50	1.5	0	0	100	2.0							0	0	100	2.0		0	2	98	2.0																
ES-03-S-9404																				0	0	100	2.0							0	0	100	2.0		0	29	71	1.7																
ES-04A-S-9404																0	52	48	1.5	0	86	14	1.1		0	0	100	2.0		0	90	10	1.1		0	40	60	1.6																
ES-04D-S-9404											0	100	0	1.0		0	97	3	1.0	0	73	27	1.3							0	43	57	1.6		0	88	13	1.1																0	100	0	1.0
ES-04E-S-9404	0	100	0	1.0							0	100	0	1.0		0	76	24	1.2	0	91	9	1.1		0	100	0	1.0		0	67	33	1.3		0	100	0	1.0		0	25	75	1.8												
ES-04F-S-9404											0	0	100	2.0		0	81	19	1.2	0	0	100	2.0							0	36	64	1.6		0	71	29	1.3	0	33	67	1.7												
ES-05-S-9405																0	25	75	1.8	0	0	100	2.0							0	0	100	2.0		0	3	97	2.0																
ES-08-S-9405																0	100	0	1.0						0	100	0	1.0		0	21	79	1.8																				
ES-09-S-9406																0	100	0	1.0	0	0	100	2.0							0	0	100	2.0		0	10	90	1.9																
ES-10-S-9407																														0	0	100	2.0		0	2	98	2.0																
ES-11-S-9408																														0	0	100	2.0																				
ES-15-S-9418																				0	0	100	2.0							0	0	100	2.0		0	12	88	1.9																
ES-17-S-9421																0	5	95	2.0	0	0	100	2.0							0	0	100	2.0		0	17	83	1.8																
ES-18-S-9421						0	40	60	1.6							2	97	2	1.0	0	100	0	1.0							0	43	57	1.6		0	99	1	1.0																

"M" = mean

Table 2 C. Bioerosion

	Nuculana pernula				*Portlandia arctica*				*Musculus sp.*				*Astarte sp.*				*Serripes*				*Macoma sp.*				*Mya truncata*				*Hiatella arctica*				*Thracia myopsis*				*Pandora glacialis*				*Buccinum sp.*			
Taphonomic grade	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M
ES-Sh2-0707													100	0	0	0.0																												
ES-Sh3-0807													0	100	0	1.0					0	100	0	1.0	67	33	0	0.3	89	11	0	0.1												
ES-Sh4-0807													33	67	0	0.7	100	0	0	0.0					89	11	0	0.1	58	42	0	0.4												
ES-Sh5a-0807					80	20	0	0.2					92	8	0	0.1	100	0	0	0.0	64	36	0	0.4	67	33	0	0.3	83	17	0	0.2												
ES-Sh5b-0807													88	13	0	0.1	0	100	0	1.0	92	8	0	0.1	67	33	0	0.3	100	0	0	0.0												
ES-Sh6-0807																									100	0	0	0.0																
ES-Sh8-0802					100	0	0	0.0																																				
ES-Sh9-0907													100	0	0	0.0	60	40	0	0.4					100	0	0	0.0	88	13	0	0.1												
ES-Sh10-0907									100	0	0	0.0	100	0	0	0.0													0	100	0	1.0	50	50	0	0.5								
ES-Sh17-0907													89	11	0	0.1	75	25	0	0.3					71	29	0	0.3	100	0	0	0.0												
ES-Sh18-0907																	25	75	0	0.8	50	50	0	0.5																				
ES-Sh19-0907																									0	100	0	1.0																
ES-Sh20-0907																	0	100	0	1.0					0	100	0	1.0																
ES-Sh21-0907													86	14	0	0.1	89	11	0	0.1					100	0	0	0.0																
ES-Sh22-0907									0	100	0	1.0	100	0	0	0.0	60	40	0	0.4					50	50	0	0.5																
ES-Sh23-0907													100	0	0	0.0																												
ES-Sh24-0907													100	0	0	0.0																												
ES-Sh25-1007																																												
ES-Sh27-1207	100	0	0	0.0					100	0	0	0.0	93	7	0	0.1	39	49	12	0.7	33	67	0	0.7	55	45	0	0.4	63	37	0	0.4	100	0	0	0.0	0	100	0	1.0	33	67	0	0.7
ES-Sh28-1207									100	0	0	0.0	100	0	0	0.0	25	75	0	0.8																	0	100	0	1.0	100	0	0	0.0
ES-Sh29-1207													87	13	0	0.1									94	6	0	0.1	77	23	0	0.2												
ES-Sh30-1207													88	12	0	0.1	40	60	0	0.6					91	9	0	0.1	88	13	0	0.1												
ES-Sh31-1207									100	0	0	0.0	91	9	0	0.1	67	33	0	0.3					90	10	0	0.1	82	18	0	0.2												
ES-Sh32-1207													100	0	0	0.0					0	100	0	1.0																				
ES-Sh33-1207													0	100	0	1.0									0	100	0	1.0	0	33	67	1.7												
MF-12-S-2998													100	0	0	0.0									100	0	0	0.0	100	0	0	0.0												
MF-13-S-2998																									100	0	0	0.0	100	0	0	0.0												
MF-14-S-3098																									100	0	0	0.0																
MF-16-S-0198																									100	0	0	0.0	100	0	0	0.0												
MF-18-S-0298					97	3	0	0.0					99	1	0	0.0													100	0	0	0.0												
MF-19-S-0298													100	0	0	0.0	100	0	0	0.0					75	25	0	0.3																
MF-20-S-0398																	100	0	0	0.0					100	0	0	0.0	100	0	0	0.0												
MF-21-S-0498																									100	0	0	0.0																
MF-23-S-0598													88	12	0	0.1	100	0	0	0.0					100	0	0	0.0	100	0	0	0.0												
MF-26A/S-0898																																												
MF-26C/S-0898																																												
MF-26D/S-0898					100	0	0	0.0																																				
MF-26E/S-0898					100	0	0	0.0																																				
MF-27-S-0998									100	0	0	0.0	69	30	1	0.3	74	26	0	0.3	100	0	0	0.0	100	0	0	0.0	86	14	0	0.1												
MF-28-S-0998													91	9	0	0.1	57	43	0	0.4					63	38	0	0.4	53	47	0	0.5												
MF-29-S-0998	100	0	0	0.0					100	0	0	0.0	79	21	0	0.2	14	86	0	0.9					89	11	0	0.1	79	21	0	0.2												
ES-01-S-9402													91	9	0	0.1	93	7	0	0.1					94	1	5	0.1	54	29	17	0.6												
ES-03-S-9404																	100	0	0	0.0					92	8	0	0.1	79	21	0	0.2												
ES-04A-S-9404													87	13	0	0.1	79	21	0	0.2	100	0	0	0.0	100	0	0	0.0	70	30	0	0.3												
ES-04D-S-9404									100	0	0	0.0	100	0	0	0.0	95	5	0	0.0					86	14	0	0.1	100	0	0	0.0									100	0	0	0.0
ES-04E-S-9404	100	0	0	0.0					100	0	0	0.0	95	5	0	0.0	100	0	0	0.0	0	100	0	1.0	67	0	33	0.7	57	43	0	0.4	25	75	0	0.8								
ES-04F-S-9404									100	0	0	0.0	98	2	0	0.0	96	4	0	0.0					100	0	0	0.0	100	0	0	0.0	33	67	0	0.7								
ES-05-S-9405													25	75	0	0.8	100	0	0	0.0					55	20	25	0.7	43	43	14	0.7												
ES-08-S-9405													86	14	0	0.1					100	0	0	0.0	50	50	0	0.5																
ES-09-S-9406													20	50	30	1.1	50	50	0	0.5					69	12	19	0.5	62	31	7	0.4												
ES-10-S-9407																									50	0	50	1.0	42	46	12	0.7												
ES-11-S-9408																									100	0	0	0.0																
ES-15-S-9418																	83	17	0	0.2					82	9	9	0.3	82	18	0	0.2												
ES-17-S-9421													82	18	0	0.2	75	25	0	0.3					80	20	0	0.2	100	0	0	0.0												
ES-18-S-9421					80	20	0	0.2					77	23	0	0.2	100	0	0	0.0					83	16	1	0.2	97	3	0	0.0												

"M" = mean

Table 2 D. Encrustation

	Nuculana pernula				*Portlandia arctica*				*Musculus sp.*				*Astarte sp.*				*Serripes*				*Macoma sp.*				*Mya truncata*				*Hiatella arctica*				*Thracia myopsis*				*Pandora glacialis*				*Buccinum sp.*			
Taphonomic grade	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M	"0"	"1"	"2"	M
ES-Sh2-0707													100	0	0	0.0																												
ES-Sh3-0807													0	100	0	1.0					0	100	0	1.0	33	67	0	0.7	47	53	0	0.5												
ES-Sh4-0807													100	0	0	0.0	100	0	0	0.0					59	41	0	0.4	42	50	8	0.7												
ES-Sh5a-0807					100	0	0	0.0					42	58	0	0.6	100	0	0	0.0	73	18	9	0.4	78	22	0	0.2	100	0	0	0.0												
ES-Sh5b-0807													57	43	0	0.4	100	0	0	0.0	42	58	0	0.6	100	0	0	0.0	67	33	0	0.3												
ES-Sh6-0807																									0	100	0	1.0																
ES-Sh8-0802					100	0	0	0.0																																				
ES-Sh9-0907													33	50	17	0.8	20	80	0	0.8					50	50	0	0.5	50	50	0	0.5												
ES-Sh10-0907									100	0	0	0.0	0	100	0	1.0													50	50	0	0.5	50	50	0	0.5								
ES-Sh17-0907													53	47	0	0.5	75	25	0	0.3					14	86	0	0.9	0	100	0	1.0												
ES-Sh18-0907																	100	0	0	0.0	100	0	0	0.0																				
ES-Sh19-0907																									0	100	0	1.0																
ES-Sh20-0907																	50	50	0	0.5					100	0	0	0.0																
ES-Sh21-0907													57	43	0	0.4	44	56	0	0.6					0	100	0	1.0																
ES-Sh22-0907									100	0	0	0.0	80	20	0	0.2	40	60	0	0.6					25	75	0	0.8																
ES-Sh23-0907													50	50	0	0.5																												
ES-Sh24-0907													100	0	0	0.0																												
ES-Sh25-1007																																												
ES-Sh27-1207	100	0	0	0.0					100	0	0	0.0	76	24	0	0.2	82	16	2	0.2	100	0	0	0.0	85	15	0	0.1	45	55	0	0.5	0	100	0	1.0	100	0	0	0.0	100	0	0	0.0
ES-Sh28-1207									100	0	0	0.0	60	40	0	0.4	100	0	0	0.0																	100	0	0	0.0	100	0	0	0.0
ES-Sh29-1207													100	0	0	0.0									83	17	0	0.2	62	38	0	0.4												
ES-Sh30-1207													84	16	0	0.2	60	40	0	0.4					91	9	0	0.1	25	75	0	0.8												
ES-Sh31-1207									100	0	0	0.0	73	27	0	0.3	100	0	0	0.0					40	60	0	0.6	47	53	0	0.5												
ES-Sh32-1207													31	69	0	0.7					100	0	0	0.0																				
ES-Sh33-1207													0	100	0	1.0									67	33	0	0.3	33	67	0	0.7												
MF-12-S-2998													89	0	11	0.2									100	0	0	0.0	100	0	0	0.0												
MF-13-S-2998																									100	0	0	0.0	100	0	0	0.0												
MF-14-S-3098																									100	0	0	0.0																
MF-16-S-0198																									100	0	0	0.0	100	0	0	0.0												
MF-18-S-0298					100	0	0	0.0					43	56	1	0.6													100	0	0	0.0												
MF-19-S-0298													100	0	0	0.0	100	0	0	0.0					100	0	0	0.0																
MF-20-S-0398																	100	0	0	0.0					67	33	0	0.3	100	0	0	0.0												
MF-21-S-0498																									100	0	0	0.0																
MF-23-S-0598													100	0	0	0.0	100	0	0	0.0					100	0	0	0.0	100	0	0	0.0												
MF-26A/S-0898																																												
MF-26C/S-0898																																												
MF-26D/S-0898					100	0	0	0.0																																				
MF-26E/S-0898					100	0	0	0.0																																				
MF-27-S-0998									0	100	0	1.0	49	50	1	0.5	51	47	2	0.5	100	0	0	0.0	48	52	0	0.5	38	62	0	0.6												
MF-28-S-0998													76	24	0	0.2	43	57	0	0.6					81	19	0	0.2	47	53	0	0.5												
MF-29-S-0998	100	0	0	0.0					100	0	0	0.0	70	30	0	0.3	100	0	0	0.0					94	6	0	0.1	85	15	0	0.1												
ES-01-S-9402													41	38	22	0.8	40	40	20	0.8					67	27	6	0.4	37	54	9	0.7												
ES-03-S-9404																	33	67	0	0.7					75	24	1	0.3	71	29	0	0.3												
ES-04A-S-9404													84	16	0	0.2	100	0	0	0.0	100	0	0	0.0	100	0	0	0.0	100	0	0	0.0												
ES-04D-S-9404									100	0	0	0.0	95	5	0	0.0	100	0	0	0.0					100	0	0	0.0	100	0	0	0.0									100	0	0	0.0
ES-04E-S-9404	100	0	0	0.0					100	0	0	0.0	98	2	0	0.0	100	0	0	0.0	100	0	0	0.0	100	0	0	0.0	86	0	14	0.3	100	0	0	0.0								
ES-04F-S-9404									100	0	0	0.0	65	34	1	0.4	94	6	0	0.1					100	0	0	0.0	100	0	0	0.0	100	0	0	0.0								
ES-05-S-9305													0	75	25	1.3	100	0	0	0.0					25	70	5	0.8	14	77	9	0.9												
ES-08-S-9405													71	29	0	0.3					100	0	0	0.0	93	7	0	0.1																
ES-09-S-9406													10	70	20	1.1	100	0	0	0.0					31	63	6	0.8	52	48	0	0.5												
ES-10-S-9408																									33	50	17	0.8	37	54	9	0.7												
ES-11-S-9408																									100	0	0	0.0																
ES-15-S-9418																	67	33	0	0.3					45	55	0	0.5	36	64	0	0.6												
ES-17-S-9421													65	34	2	0.4	50	50	0	0.5					66	34	0	0.3	67	33	0	0.3												
ES-18-S-9421					40	60	0	0.6					30	67	3	0.7	100	0	0	0.0					78	22	0	0.2	89	11	0	0.1												

"M" = mean

Appendix II: Systematic Descriptions of Species And Statistical Analysis Output

A. Systematic List of 27 Identified Taxa in This Study

Class: BIVALVIA

Order: Nuculoida
Family: Nuculidae
Nucula (Ennucula) belloti (Adams, 1856)

Family: Nuculanidae
Nuculana pernula (Müller, 1779)

Family: Sareptidae
Portlandia arctica (J.E. Gray, 1824)

Order: Mytiloida
Family: Mytilidae
Musculus corrugatus (Stimpson, 1851)
Musculus discors (Linnaeus, 1767)
Musculus niger (J.E. Gray, 1824)

Order: Veneroida
Family: Thyasiridae
Thyasira gouldi (Philippi, 1845)

Family: Astartidae
Astarte borealis (Schumacher, 1817)
Astarte montagui (Dillwyn, 1817)

Family: Cardiidae
Clinocardium ciliatum (Fabricius, 1780)
Serripes groenlandicus (Mohr, 1786)

Family: Tellinidae
Macoma calcarea (Gmelin, 1791)
Macoma loveni (A.S. Jensen, 1905)
Macoma moesta (Deshayes, 1855)

Order: Myoida
Family: Myidae
Mya truncata Linnaeus, 1758
Mya pseudoarenaria Schlesch,

Family: Hiatellidae
Hiatella arctica (Linnaeus, 1767)

Order: Pholadomyoida
Family: Lyonsiidae
Lyonsia arenosa (Møller, 1842)

Family: Pandoridae
Pandora glacialis (Leach, 1819)

Family: Thraciidae
Thracia myopsis (Møller, 1842)

Class: GASTROPODA

Order: Archaeogastropoda
Family: Trochidae
Margarites olivaceous (T. Brown, 1827)

Order: Neotaenioglossa
Family: Capulidae
Trichotropis borealis Broderip and G.B. Sowerby I, 1829

Order: Neogastropoda
Family: Buccinidae
Buccinum sp.
Colus sp.

Family: Conidae
Oenopota cf. *cinerea* (Møller, 1842)

Order: Cephalaspidea
Family: Cylichnidae
Cylichna sp.

B. Utility of the Statistical Methods

Cluster analysis and MDS are both methods of classification which can be used to analyze multivariate data. Groups can be produced directly by the clustering method, but results may vary significantly with different linkage methods. In this study we use between-group linkage to produce clusters, which avoided chaining problems that occur when using within-group linkage. At the same time, clustering analysis using presence-absence binary data is also sensitive to rare taxa. MDS should have the same problem with respect to sensitivity, but the direct result of scaling is to demonstrate distribution patterns in the data: this type of analysis will not produce any groups directly. The groups of samples can be recognized by investigating the dimension values of the samples and comparing the distance between each sample in the derived two/three dimensional space. However, it is difficult for an operator to analyze the results of MDS when 3 or more dimensions are produced as the result becomes more complex with additional dimensions.

Coefficients of distances for the squared distance matrix in MDS process are described by the stress value and squared correlation coefficient (RSQ) listed in Appendix II C, which are the outputs of two goodness-of-fit tests. The stress value is derived from Kruskal's stress formula 1 (see SPSS Inc., 1988, 2003). It is used to compute the sum of squared deviations of observed distances (or some monotonic transformation of those distances) from the reproduced distances. Thus, the smaller the stress value, the better is the fit of the reproduced distance matrix to the observed distance matrix. The value for scaling of taxa (Figure 5.2) is a little bit larger than 0.2, which means the derived model becomes increasingly inaccurate or the fit is not very

good. RSQ is the proportion of variance of the scaled data (disparities) in the partition (raw, matrix, or entire data) that is accounted for by their corresponding distances (see SPSS Inc., 1988, 2003). This value can reflect the degree to which the data distribution is interpreted by the derived model. In this case, a value of 0.6981 is not very high but it can still be accepted, because the distribution exhibits ecological meaning and is comparable to the results of cluster analysis. If the data were portrayed by a 3-dimensional solution, more of variance in the data would be interpreted in the derived model and therefore, the goodness-of-fit measures would likely display a smaller stress value and a larger RSQ. The data matrix used in this study may be a combination of many characters such as life habit, feeding mode, locomotion, substrate type, depth range, salinity, temperature, geographic distribution, etc., so a 3-dimensional solution would probably be superior to a 2-dimensional solution for portraying the data distribution in MDS. However, 2- dimensional space is clearer for presenting and comparing results, and it would be hard to study or interpret data distributions in 3-dimensional space. Stress values and RSQ for MDS on samples show similar problems (Appendix II D), though the stress value is lower and the RSQ is larger. This slight improvement is probably due to relatively fewer and simpler variables (11 taxa) that affect the derived dimensions. The optimal solution differs from one study to another, and an advanced statistical method still needs to be discovered to prevent compromising the number of dimensions in order to improve accuracy of simulation.

C. Output of MDS by SPSS v12.0 on 11 species

Proximities

Case Processing Summary[b]

Cases							
		Rejected					
Valid		Missing Value		Out of Range Binary Value[a]		Total	
N	Percent	N	Percent	N	Percent	N	Percent
55	100.0%	0	.0%	0	.0%	55	100.0%

a. Value different from both 1 and 0.

b. Binary Lance-and-Williams Nonmetric Measure used

Alscal

```
Iteration history for the 2 dimensional solution (in squared distances)

                Young's S-stress formula 1 is used.

              Iteration     S-stress      Improvement

                  1           .39820
                  2           .32197         .07623
                  3           .31965         .00232
                  4           .31883         .00082

                     Iterations stopped because
               S-stress improvement is less than   .001000


           Stress and squared correlation (RSQ) in distances

RSQ values are the proportion of variance of the scaled data
(disparities)
          in the partition (row, matrix, or entire data) which
           is accounted for by their corresponding distances.
            Stress values are Kruskal's stress formula 1.


                For  matrix
    Stress  =   .28242      RSQ =  .65407
```

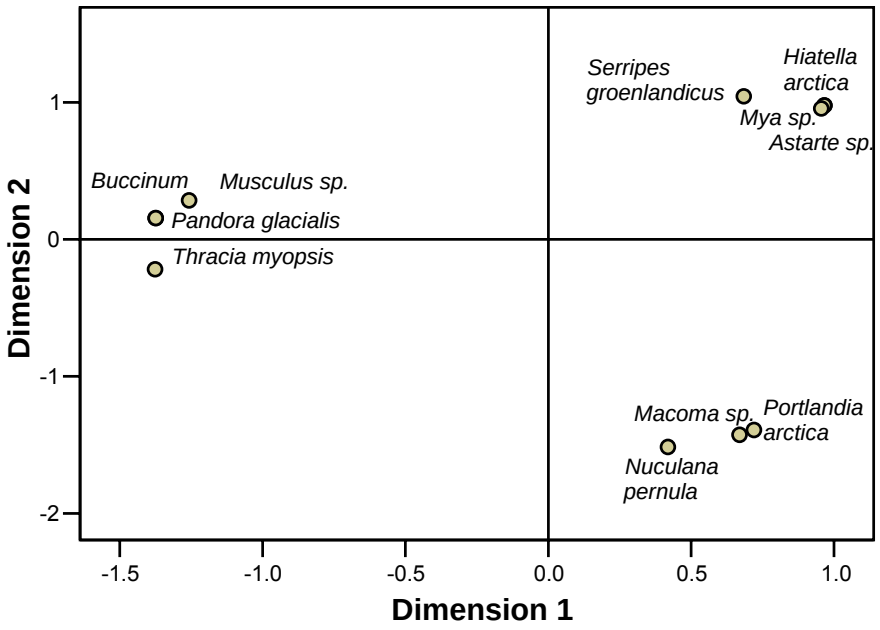
Configuration derived in 2 dimensions

Stimulus Coordinates Dimension

Stimulus Number	Stimulus Name	1	2
1	Hiatella	.9665	.9776
2	Mya_sp	.9660	.9779
3	Serripes	.6843	1.0447
4	Astarte_	.9557	.9557
5	Macoma_s	.7199	-1.3912
6	Portland	.6696	-1.4264
7	Musculus	-1.2569	.2845
8	Nuculana	.4187	-1.5156
9	Thracia	-1.3761	-.2179
10	Pandora	-1.3739	.1554
11	Buccinum	-1.3739	.1554

Derived Stimulus Configuration

Euclidean distance model



D. Output of MDS by SPSS v12.0 on 55 samples

Proximities

Case Processing Summary[b]

Cases							
		Rejected					
Valid		Missing Value		Out of Range Binary Value[a]		Total	
N	Percent	N	Percent	N	Percent	N	Percent
12	100.0%	0	.0%	0	.0%	12	100.0%

a. Value different from both 1 and 0.

b. Binary Lance-and-Williams Nonmetric Measure used

Alscal

```
Iteration history for the 2 dimensional solution (in squared distances)

                Young's S-stress formula 1 is used.

              Iteration     S-stress      Improvement

                  1           .33691
                  2           .26267         .07424
                  3           .25868         .00399
                  4           .25824         .00044

                     Iterations stopped because
               S-stress improvement is less than   .001000


           Stress and squared correlation (RSQ) in distances

RSQ values are the proportion of variance of the scaled data
(disparities)
          in the partition (row, matrix, or entire data) which
           is accounted for by their corresponding distances.
            Stress values are Kruskal's stress formula 1.


               For  matrix
    Stress  =   .22831      RSQ =  .83112
_
```

Configuration derived in 2 dimensions

Stimulus Coordinates

Stimulus Number	Stimulus Name	Dimension 1	Dimension 2
1	ES_Sh2_0	1.3084	1.2772
2	ES_Sh3_0	-1.2802	-.5892
3	ES_Sh4_0	-.4512	.4607
4	ES_Sh5a_	.4087	-.5361
5	ES_Sh5b_	-.0581	.7743
6	ES_Sh6_0	-1.4026	-.8176
7	ES_Sh8_0	1.7196	-2.0639
8	ES_Sh9_0	-.3225	.4088
9	ES_Sh10_	.5053	1.2015
10	ES_Sh17_	-.3219	.4094
11	ES_Sh18_	1.9319	-.8459
12	ES_Sh19_	-1.3880	-.8298
13	ES_Sh20_	-1.1544	-.5602
14	ES_Sh21_	-.1261	.6790
15	ES_Sh22_	-.0752	.7576
16	ES_Sh23_	1.3150	1.2561
17	ES_Sh24_	1.3161	1.2552
18	ES_Sh25_	1.7256	-2.0389
19	ES_Sh27_	-.3002	.3938
20	ES_Sh28_	1.2564	1.1281
21	ES_Sh29_	-.4165	.4457
22	ES_Sh30_	-.2967	.3956
23	ES_Sh31_	-.2967	.3956
24	ES_Sh32_	1.4860	1.0689
25	ES_Sh33_	-.4116	.4480
26	MF_12_S_	1.3131	1.2513
27	MF_13_S_	-1.2398	-.5805
28	MF_14_S_	-1.3611	-.8121
29	MF_16_S_	-1.2393	-.5812
30	MF_18_S_	1.7732	-.0978
31	MF_19_S_	-.1022	.6649
32	MF_20_S_	-1.0212	-.3067
33	MF_21_S_	-1.3533	-.8156
34	MF_23_S_	-.1059	.6627
35	MF_26A_S	-.6753	-1.6681
36	MF_26C_S	1.7129	-2.0187
37	MF_26D_S	1.7129	-2.0187
38	MF_26E_S	1.7130	-2.0187
39	MF_27_S_	.4486	.8726
40	MF_28_S_	-.2668	.3576
41	MF_29_S_	-.3831	.4077
42	ES_01_S_	-1.2018	-.6193
43	ES_03_S_	-1.2018	-.6193
44	ES_04A_S	-.2691	.3554

45	ES_04D_S	-.2691	.3554
46	ES_04E_S	1.4164	1.1926
47	ES_04F_S	1.1309	1.0915
48	ES_05_S_	-.3775	.4093
49	ES_08_S_	-.2092	.6356
50	ES_09_S_	-.3772	.4086
51	ES_10_S_	-1.1951	-.6085
52	ES_11_S_	-1.3074	-.8442
53	ES_15_S_	-.9775	-.3404
54	ES_17_S_	-.3792	.4055
55	ES_18_S_	-.3792	.4055

Derived Stimulus Configuration

Euclidean distance model